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THESIS

DIGITAL SEMAPHORE: TACTICAL IMPLICATIONS OF QR CODE OPTICAL SIGNALING FOR FLEET COMMUNICATIONS

by

Stephen P. Richter

June 2013

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13. ABSTRACT

This thesis focuses on potential tactical uses of Quick Response (QR) codes for optical signaling. It examines visual communications methods used effectively by the fleet throughout history, both during peace and wartime operations. Due to the advent of new technology, radio frequency line-of-sight (RF LOS) communications have come to the forefront of current operations, leaving the fleet vulnerable when conducting operations in an emissions controlled (EMCON) environment. In addition, the use of QR codes can circumvent the issues associated with Hazards of Electromagnetic Radiation to Ordinance (HERO) as well as provide a new effective method for conducting Identification Friend Foe/Neutral (IFFN). The ultimate goal of this thesis is to initiate new efforts that provide the fleet with an option for a new visual communication method. The need for a reliable visual line-of-sight (LOS) communications method has become apparent.

This work proposes the tactical use of QR codes for visual communications, conveniently described as "Digital Semaphore." QR codes have the ability to become the newest and most effective method of visual communication, replacing older, less effective forms. This thesis examines the use of various sensors and cameras to read and decode QR codes, and also proposes new practical uses of QR codes for communications on board ships, aircraft, and unmanned vehicles. Prototype software is provided as an initial-candidate QR Tactical Decision Aid (TDA). The ultimate goal of this thesis is to provide the fleet with an option for a visual communications method that allows ships and other units operating in a tactical emissions controlled environment to minimize communications vulnerability and maximize operational effectiveness.

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DIGITAL SEMAPHORE: TACTICAL IMPLICATIONS OF QR CODE OPTICAL SIGNALING FOR FLEET COMMUNICATIONS

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This work proposes the tactical use of QR codes for visual communications, conveniently described as “Digital Semaphore.” QR codes have the ability to become the newest and most effective method of visual communication, replacing older, less effective forms. This thesis examines the use of various sensors and cameras to read and decode QR codes, and also proposes new practical uses of QR codes for communications on board ships, aircraft, and unmanned vehicles. Prototype software is provided as an initial-candidate QR Tactical Decision Aid (TDA). The ultimate goal of this thesis is to provide the fleet with an option for a visual communications method that allows ships and other units operating in a tactical emissions controlled environment to minimize communications vulnerability and maximize operational effectiveness.

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LIST OF ACRONYMS AND ABBREVIATIONS

2D	Two Dimensional
A2AD	Anti-Access Area Denial
AAV	Amphibious Assault Vehicle
AIM	Association for Automatic Identification & Mobility
ARSENL	Advanced Robotic Systems Engineering Laboratory
BMD	Ballistic Missile Defense
BTB	Bridge-to-Bridge
CIWS	Close-in Weapons System
CO	Commanding Officer
COTS	Commercial off the Shelf
CRUSER	Consortium for Robotics and Unmanned Systems Education and Research
CSG	Carrier Strike Group
EM	Electromagnetic
EMCON	Emissions Control
ESG	Expeditionary Strike Group
EW	Electronic Warfare
FOV	Field of View
HERO	Hazards of Electromagnetic Radiation to Ordinance
HF	High Frequency
HHQ	Higher Headquarters
HVU	High Value Unit
IFFN	Identification Friend or Foe/Neutral
ILE	In-line Encryption

ISO	International Standards Organization
JIS	Japanese Industrial Standards
KHz	Kilohertz
LARC	Lighter, Amphibious Supply, Cargo
LCAC	Landing Craft Air Cushion
LCU	Landing Craft, Utility
LOS	Line-of-Sight
LPD	Low Probability of Detection
LPE	Low Probability of Exploitation
LPI	Low Probability of Intercept
MHz	Megahertz
MOVES	Modeling, Virtual Environments and Simulation
NATO	North Atlantic Treaty Organization
QPSK	Quadrature Phase Shift Keying
QR	Quick Response
RF	Radio Frequency
SRBOC	Super Rapid Bloom Off-Board Chaff
UAV	Unmanned Aerial Vehicle
UHF	Ultra High Frequency
UPC	Universal Product Code
URL	Uniform Resource Locator
USV	Unmanned Surface Vehicle
VBSS	Visit Board Search and Seizure
VHF	Very High Frequency
X3D	Extensible 3D Graphics International Standard

GLOSSARY

Alignment Pattern. The small bullseye patterns appearing in QR code versions 2 and greater allowing for optical alignment of codes with linear and non-linear distortions.

Anti-Access/Area Denial. Enemy actions which inhibit military movement into a theater of operations, and activities that seek to deny freedom of action within areas under the enemy's control.

CCD. A device that is used to convert reflected light into an electrical signal. A charge-transfer device used as an image sensor in which the image-representing electrical charge is moved, usually from within the device to an area where the charge can be manipulated.

CMOS. Integrated circuit sensors where multiple active transistors represent each pixel allowing for on-chip processing.

De-Bayering. The use of a 50% green, 25% red, and 25% blue pattern to reconstruct image sensor data into a viewable, color image.

Dynamic Range (DR). The ratio between the maximum and minimum measurable light intensities (white and black). The ratio between the maximum signal and the rms noise.

Emissions Control (EMCON). The control of all electromagnetic and acoustic radiations, including communications, radar, EW and sonar. During its imposition, no electronic emitting device within designated bands, including personal communication devices, will be operated unless absolutely essential to the mission.

Encryption. A process to ensure data or information is read or used only by its intended readers or users.

Error Correcting Code (ECC). A code in which each group of characters or signals conforms to specific rules of construction so that departures from this construction in the received signals can be automatically detected and some or all of the errors can be automatically corrected.

Finder Pattern. The large bullseye pattern located at three corners of a QR code specifying the location of the encoded data.

Flight Deck Operations. The launching, landing, or refueling of aircraft on board surface ships.

Focal Length. The distance between the center of a convex lens or concave mirror and the focal point of the lens or mirror that determines how much magnification it provides.

f-stop. The measurement of the aperture setting in a camera lens that determines how much light is allowed to enter the lens and pass through to the CCD or CMOS sensor.

Hazards of Electromagnetic Radiation to Ordnance (HERO). The program concerned with prevention of accidental ignition of electrically initiated devices (EID's) in ordnance due to RF electromagnetic fields.

Line-of-Sight. A direct propagation path that does not go below the radio horizon.

Long Wave Infrared. The range of invisible radiation wavelengths from 750 nanometers (just longer than red in the visible spectrum), to 1 millimeter (on the border of the microwave region).

Low Probability of Detection. The result of measures put in place to disguise or hide intentional electromagnetic transmissions.

Low Probability of Exploitation. Preventing the exploitation of a signal by denying the adversary knowledge of the system, its modulation characteristics, its use and its users.

Low Probability of Intercept. Putting measures in place in order to ensure the interception of signals and messages is not achievable.

Multipath Effects. The propagation phenomenon which results in a time delay due to the radio signals reaching the receiving antenna by two or more paths. Causes of multipath effects include ionospheric reflection, refraction, atmospheric ducting, and reflection from water, buildings, and mountains.

Obfuscation. The hiding of intended meaning in communication, making communication confusing, willfully ambiguous, and harder to interpret.

QR Bit. The smallest structure within a QR code representing a one (black) or zero (white).

QR Code. A two dimensional barcode developed by the Denso Wave corporation in the 1990s for the Japanese automotive manufacturing industry.

Reed-Solomon Error Correction. An error-correcting code that oversamples a polynomial constructed from the data and the polynomial is evaluated at several different points. This oversampling causes the polynomial to be over-determined, which allows the receiver to recover the original polynomial with enough points received correctly.

Resolution. The number of pixels contained on a display monitor, expressed in terms of the number of pixels on the horizontal axis and the number on the vertical axis. This helps determine the sharpness of an image.

Semaphore. Visual signaling in which the positions of the hands each holding a flag are used to represent letters of the alphabet, numerals, punctuation, and certain procedure words and prosigns that are used for the transmission of messages.

Timing Pattern. Alternating black and white modules in a QR code that assist the decoder application in detecting the position of each cell in the QR code.

Well Deck Operations. The launching and recovery of amphibious assault craft from a surface ship.

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Last, I would like to take this time to extend a personal thank you and gratitude to LCDR Andy Lucas, for tackling the QR code thesis topic with me. Without your friendship, work ethic, and motivation, I am not sure I would have completed a thesis during my time here at NPS. Thank you for all of your help and mentorship.

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I. INTRODUCTION

A. ABSTRACT

This thesis examines visual communications methods used effectively by the fleet throughout history, both during peace and wartime operations. Due to the advent of new technology, radio frequency line-of-sight (RF LOS) communications have come to the forefront, leaving the fleet vulnerable when conducting operations in an emissions controlled environment. The need for a reliable visual line-of-sight communications method has become apparent. The use of QR codes for visual communications has been coined “Digital Semaphore.” QR codes have the ability to become the newest and most effective method of visual communication, replacing older, more outdated forms. This thesis examines the use of various sensors and cameras to read and decode QR codes as well as discusses theoretical uses of QR codes for communications on board ships, aircraft, and unmanned vehicles. The ultimate goal of this thesis is to provide the fleet with an option for a new visual communication method that allows ships and other units operating in a tactical and emissions-controlled environment to maintain operational effectiveness.

B. PROBLEM STATEMENT

Ultra-high Frequency (UHF) and Very-high Frequency (VHF) LOS communications are common throughout the world and an adversary can easily acquire equipment with which they may be able to intercept or attempt to jam naval communications. Additionally, tactical units operating in an emission-restricted environment creates the need for a visual communications method to augment RF LOS communications methods. This has serious implications for communications between naval ships, naval aircraft, and unmanned systems.

Further, Emissions Control (EMCON) and Hazards of Electromagnetic Radiation to Ordnance (HERO) restrict the ability for Naval Vessels to communicate using traditional radio frequency communications.

C. SOLUTION OVERVIEW

Figure 1 illustrates the many possible uses and tactical implementations of QR codes as a visual communication method. Ships can use QR codes for communication as well as for different evolutions such as underway replenishment and flight operations. QR codes can be used to transmit and receive messages via line-of-sight communication between aircraft, unmanned aerial vehicles, and ships. Aircraft can receive vital information from a QR displayed on a control tower or the runway itself and tactical units operating covertly can transmit messages to aircraft and unmanned aerial vehicles. As indicated in Figure 1, there are only two instances where radio frequencies must be transmitted, which indicate that QR codes for communication can be effective while operating in an emissions controlled (EMCON) environment and ultimately restore EMCON as a feasible tactical condition.

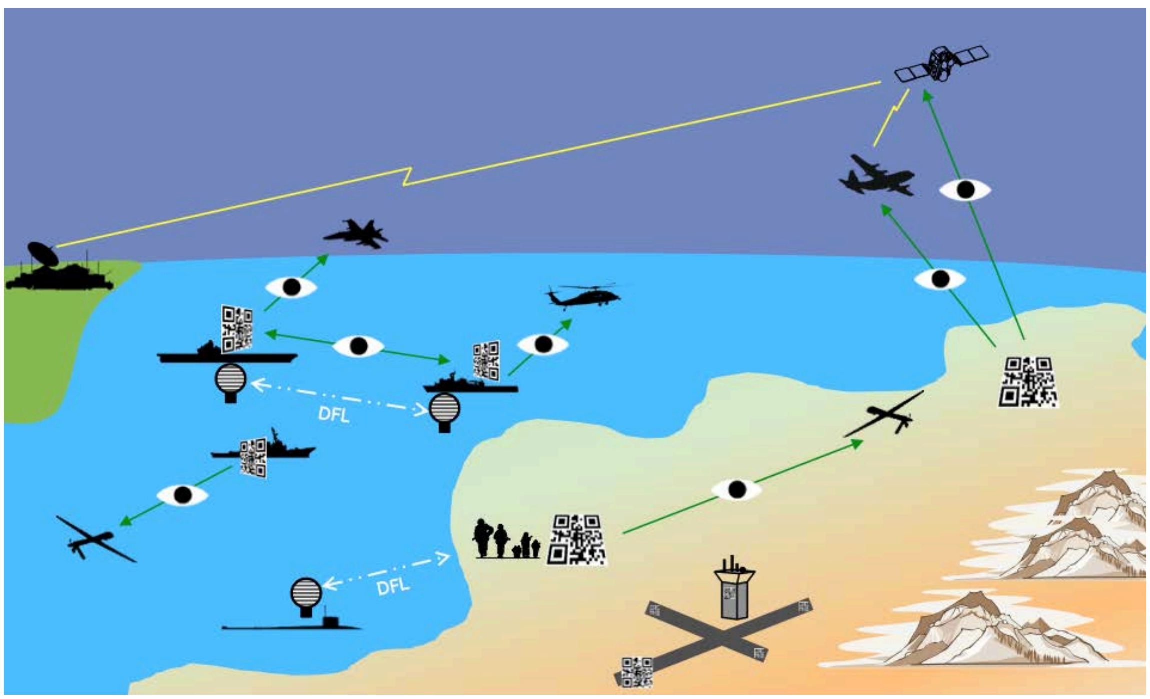

Figure 1. Operational concept graphic of the tactical implementation of QR codes as a visual communication method. QR codes allow Emissions Control to be achieved for a full range of in-theater fleet tactical operations.

EMCON can be achieved for a full range of fleet in-theater tactical operations and activities by utilizing QR codes as a communication method. The following is a list of potential tactical use cases which correspond to Figure 1.

- Ship-to-ship communications to include tactical maneuvering and underway replenishment.
- Ship-to-aircraft communications and vice versa. Helicopters and aircraft can receive vital information via this visual communications link in the battle space.
- Aircraft and helicopters receive and transmit messages from ground units. Additionally, airstrips and control towers have the ability to communicate important information.
- UAV's extend the range of QR codes by acting as a relay in the sky.
- Digital Flashing Light, which is discussed later, is a future work item that will extend the range and effectiveness of existing flashing light communications.

D. PURPOSE AND MOTIVATION

Once prominent in tactical situations, visual communications between naval units has become somewhat of a lost art and is rarely utilized or taught to sailors in the Fleet. Flag semaphore; flashing light, and flag hoist communications have proved to be instrumental in tactical naval victories throughout history. Over time, visual communications have been put on the back burner in favor of voice communications, which are not as effective in Emissions Controlled or Anti-Access Area Denial (A2AD) situation. Line-of-sight (LOS) RF communications systems are left vulnerable to jamming and interception. Without visual communications capabilities, tactical communications may become non-existent in cases when the most restrictive types of emissions restrictions are required to be in place.

The promising results of this QR code research shows that further work needs to be conducted in order to ensure that future communications between tactical units are more covert, will be extremely difficult to jam, can be decoded in a timely manner, and can be conducted in an emissions restricted or denied environment. This type of digital communications can also allow for the military to communicate quickly and effectively as an alternative to LOS voice communications. Ultimately, the fleet needs to be sure that tactical communications between units are safe, secure and efficient, which makes this research relevant and important for the future of the fleet.

E. RESEARCH QUESTIONS AND HYPOTHESIS

1. Research Questions

- Why is this method of information transfer better than RF LOS communications?
- What tactical advantages are given by QR codes that are not given by RF LOS?
- What tactical disadvantages can be experienced by QR code communications?
- How will this capability improve tactical performance for various platforms?
- What capabilities will this system provide beyond naval applications?
- Does the probability of detection become drastically reduced when communicating with QR codes vice using existing RF LOS voice communications?
- What methods of data transmission are feasible in a visually precluded environment (i.e., fog, line-of-sight obstruction)?
- Which environments are permissive and non-permissive for QR code communications?

2. Hypothesis

QR code communications can allow for ships operating in a tactical environment to have discrete and virtually undetectable communications. This will enable effective and efficient tactical communications between units operating in an emissions restricted environment for the fleet and its allies and will reduce the probability of detection by adversaries.

F. METHODOLOGY

Research will include modeling, simulation and field experimentation. The project is building a library of exemplar quick response (QR) codes and software routines for testing and evaluation. Simulation and modeling compares radio frequency emitters and QR code displays in various tactical scenarios. This can show the situations in which

QR code communications are superior to traditional methods in terms of detection and intercept. Field experimentations will be conducted to analyze the benefits of various technologies in an end-to-end assessment of the QR communication chain. This can identify the ideal technologies required to implement this method with acceptable performance parameters tactically.

Experimentation included conducting baseline analysis of different camera technologies and their abilities to read QR codes at various ranges. Testing included distance experimentation with multiple cameras, satellite imagery pixel detection using a painted QR code on the roof of King Hall at NPS, satellite imagery QR code detection, and unmanned aerial vehicle QR code detection at Camp Roberts. Angle simulation was also performed in order to determine the maximum angle at which a QR code can be read effectively based on the camera being used and the distance at which the QR code was displayed.

G. SCOPE

This research includes experiments to validate the use of QR codes in a tactical environment. Initial testing establishes a baseline for performance expectations using standard COTS optical and software equipment to generate, capture and decode static QR images. Further experimentation places these static QR codes into more dynamic situations to verify the baseline expectations hold consistent in changing conditions. Finally, experimentation attempts to establish the capability to capture and decode a sequence of streaming QR codes. The ability to capture and decode streaming QR codes can provide the fleet with additional capability to be able to transfer larger amounts of data.

H. THESIS ORGANIZATION

This thesis discusses the feasibility and benefits of introducing visual communications using QR codes tactically between naval units. It explores the various types of cameras available to read QR codes and will determine effective ranges at which each camera can read various pixel sizes. It discusses the historical benefits of visual communications in the tactical environment as well as the improved communications capabilities experienced by utilizing QR codes between naval units in an emission controlled or emissions restricted environment. In addition, the importance of visual communications methods is brought to light by discussing emissions control, hazards of electromagnetic radiation to ordnance, and anti-access area denial (A2AD) environments.

Chapter II summarizes and describes the QR code project overview and other related work pertinent to this thesis. Chapter III is an overview of the various types of visual communications methods utilized by the fleet throughout history. Chapter IV discusses existing RF LOS communications techniques used in the fleet today, to include high frequency, very-high frequency, and ultra-high frequency communications. Chapter V is an overview and description of one-dimensional bar codes, two-dimensional bar codes, and QR codes. Chapter VI is an overview of emissions restrictions including Emissions Control (EMCON) and Hazards of Electromagnetic Radiation to Ordnance (HERO). Chapter VII is dedicated to tactical scenarios and use cases for QR codes as an optical signaling method. Chapters VIII and IX are research methods and experimental results and analysis, respectively. Chapter X concludes the thesis by drawing conclusions and providing recommendations and opportunities for future work.

Throughout this thesis, there are many times when technical aspects of QR codes and the use of camera technology are mentioned. For extensive study regarding these technologies, refer to *Digital Semaphore: Technical Feasibility of QR Code Optical Signaling for Fleet Communications* (Lucas, 2013). This document complements much of the research herein and shares several chapters. Specifically, Chapter V, One-Dimensional (1D) Bar Codes, Two-Dimensional (2D) Bar Codes, and QR Codes, Chapter VIII Research Methods, and Chapter IX, Experimental Results and Analysis are co-written. Appendix A, Experiment Schedule of Events and Appendix B, Simulation and Experiment Data are shared as well.

I. BENEFITS OF STUDY

The ultimate benefit of this thesis is to provide an alternative and jam-resistant form of fast and reliable visual line-of-sight communications to the fleet that will augment the current RF line-of-sight communications suite. This system is able to leverage many existing commercial-off-the-shelf technologies in the form of QR code reading and generation software. Additionally, QR code transmissions are platform agnostic preventing adversaries from identifying the source based on the nature of the transmission itself.

Using QR code as a form of visual communication may be vulnerable to non-permissive environments such as hazy conditions, fog, heavy seas, excessive background lighting or insufficient illumination. However, the use of QR codes for visual communications between tactical units will provide a method of communications in an RF non-permissive environment when situations call for EMCON or Hazards of Electromagnetic Radiation to Ordinance (HERO) to be employed. Unless exclusive equipment is used, any unencrypted transmissions may be vulnerable to intercept by an adversary.

This thesis can ultimately recommend the purchase of equipment to be distributed throughout the fleet in order to provide ships and other tactical units with the QR code communications capability known as digital semaphore. This work has fundamental implications for naval warfare. Literature review to date has not revealed any industry or academic efforts that are exploring these possibilities. The plan is to begin submitting patent applications to ensure that the Navy’s long-term Intellectual Property Rights (IPR) are protected.

J. CHAPTER SUMMARY

This thesis explores the use of QR codes for communications between tactical units using different camera technology. It proves the point that traditional methods of visual communication have largely been abandoned in favor or voice communications which rely upon the EM spectrum and RF transmissions. In an emission restricted environment, it is imperative to have an alternative means to communicate in order to remain undetected by adversaries. A QR code used as visual communications is the perfect solution for this issue because of the fact that these transmissions cannot be jammed or be intercepted as easily as voice transmissions. Additionally, these messages can be transmitted, received, and decoded in a short amount of time, increasing the efficiency of communications at sea.

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II. RELATED WORK AND PROBLEM DESCRIPTION

A. OVERVIEW

Work with Quick Response codes has been done through a CRUSER sponsored workshop. This work was mostly geared toward live streaming of QR codes and documenting the different capabilities that various cameras provide with regard to reading QR codes. Little has been with regard to post-processing of QR codes utilizing different types of software and applications. There has not been much documented work with regard to using QR codes for digital and visual communications. The ultimate goal for this research is to ensure that the fleet is provided with a form of visual communications to augment the current VHF and UHF line-of-sight communications that will be difficult to jam and detect, simple to use, and has low maintenance requirements. If successful, QR codes for communications can provide the fleet and other tactical units with an effective and reliable form of visual communications that can also be effective in an emissions controlled environment.

B. CRUSER WORKSHOP

Through a CRUSER sponsored workshop (Digital Semaphore, 2012), it has been noted that the ability to create and display QR codes can be achieved easily. The increasing use of online and offline QR code creation applications in industry and the availability of digital storage allow users to find encode and decode these two-dimensional bar codes with few barriers to success. However, this research has shown that QR code use for communications purposes in tactical environments will require specialized equipment, signal processing, and specific procedures in order to fully implement the technology (Digital Semaphore, 2012). Although work has been done with QR codes through CRUSER, there has not been any work or experimentation done for the purpose of utilizing QR codes for tactical communications. No work has been done to date on the implementation and feasibility of using QR codes as a visual communication method.

1. Electro Magnetic Maneuver Massive Multiplayer Online War Game (EM2 MMOWGLI)

An Electro Magnetic Maneuver Massive Multiplayer Online War Game Leveraging the Internet (EM^2 MMOWGLI) was conducted to explore the vulnerability that exists inherent to the technological nature of modern warfare (https://mmowgli.nps.edu/em2). The three phases of the game were:

- Know the EM Environment: Understanding EM Energy
- Be Agile: C2 in the EM Environment
- Paradigm Change: Tactical Employment of EM Weapons

As a result of the EM^2 MMOWGLI, five action plans focused on QR code and other means of visual communications emerged:

Action plan 25 was titled QR Code Characteristics for Optical Signaling and Streaming Transmission. This plan introduced the idea of using QR codes for optical communications between tactical environments. Action plan 27 was titled DFL for Unjammable LOS Signaling Between Navy Ships. This plan looked beyond the limitations of QR code by coupling existing light display capabilities with a system from controlling those lights for tactical communications. Action Plans 26, 39, and 40 demonstrated sound tactical applications for the use of QR codes in communications. These plans are titled: Tactical QR Code Streaming: High-Speed Optical Signaling for Fleet and Unmanned-System Communications, QR Code IFFN: Identification Friend, Foe or Neutral, and Vertical QR Message to Aircraft and Spacecraft.

The EM2 war game provided valuable input from the MMOWGLI community assessing the validity of this research (EM2 MMOWGLI, 2013).

C. PROBLEM DESCRIPTION

"The positive necessity for radio silence on the part of vessels engaged in naval operations during war cannot be emphasized too strongly. The importance of adequate means of visual communication is therefore apparent," (Lewis, 1928). This quote illustrates the importance for the fleet to maintain a form of tactical visual communications in a radio silent or emissions restricted environment. If radio silence is required, communications must still be maintained in order to ensure the vessels remain synchronized in battle. Radio silence is a method employed by tactical units in order to greatly reduce or completely avoid detection by adversaries. Although this quote comes from a book written and published almost one hundred years ago, the importance of maintaining radio silence still resonates in today's tactical environments, which leads to the necessity for visual communications to ensure a tactical advantage is established and maintained.

D. PROBLEM BACKGROUND INFORMATION

Visual communications between naval vessels at sea have become relatively obsolete and the need to remain undetectable from adversaries is essential. The fleet relies heavily upon RF LOS communications in the form of HF, VHF, and UHF, but these communications systems are vulnerable to jamming, electronic attack, interception, and are far less effective when emissions control measures are in place, which require the systems to be shut down for an unknown period of time in order to remain undetected for as long as possible.

The vulnerabilities of RF LOS communications mentioned here is evidence that the fleet needs a reliable, quick, simple, and effective visual communications method. One possible solution to this problem is implementing Quick Response codes as a sort of "Digital Semaphore" or "Tactical QR Communications." This type of visual communication can provide the fleet with an alternate means to line-of-sight radio communications and allow tactical units to greatly reduce electronic signature and probability of detection by adversaries.

E. CHAPTER SUMMARY

Work has been done with Quick Response codes through the CRUSER Lab in order to demonstrate that QR codes can be captured with still image and video cameras and then decoded using post-processing software (Digital Semaphore, 2012). This testing and experimentation is only the beginning portion of reaching the end goal of being able to utilize Quick Response Codes as a communications method in tactical environments. If successful, this new technology might provide the Fleet with a visual communication technique that will be simple to operate, require a minimum amount of training for operators of the system, and be extremely difficult to detect and jam by adversaries. Warfighters operating in tactical environments that require a covert communications method might ultimately benefit from a new method of communication, such as the use of Quick Response codes. Existing RF LOS methods of communication leave tactical units vulnerable to jamming, detection and interception by adversaries and can ultimately lead to the unit's intentions and plans compromised. Protective measures such as emissions control or radio silence might ultimately be circumvented by implementing a fast, reliable, and simple visual communications method, which provides further protection for and maintain effective command and control for the tactical unit or units in question.

III. HISTORICAL MARITIME COMMUNICATIONS AND VISUAL COMMUNICATIONS METHODS

A. CHAPTER OVERVIEW

"Tactical communications are principally orders to our own forces in contact with the enemy when maneuvering preparatory to and during engagement. The function of communications during battle is principally tactical: to assist in concentrating our attack upon a weak or exposed part of the enemy's battle line, breaking up his tactical formations and destroying his vessels, through important communications relating to tactical movements, fire control, and fire concentration," (Lewis, 1928). This quote from *A Digest of Naval Communications* defines tactical communications and illustrates the importance of maintaining tactical communications between vessels at sea engaged in battle, preparing for battle, or while executing training exercises and evolutions. This chapter will discuss the various types of tactical communications used at sea throughout history and the significance of each

Throughout history, visual communications have played a major role in naval engagements. Admiral Horatio Nelson of the British Royal Navy is famous for his service and one of the most notable battles in history; the Battle of Trafalgar. He is credited with mastering the art of tactical visual communications and was an expert in unconventional naval tactics and strategy (Lyon, 1996). Nelson was able to communicate effectively with other ships under his command using flag hoist communication. The Battle of Trafalgar demonstrated the importance of visual communications in a time where radio frequency line-of-sight communications were not yet in existence. The effectiveness with which Nelson was able to visually communicate with his fleet demonstrates the need to explore new forms of visual communications for use in today's fleet, especially given the growing threat of Anti-access Area Denial operations by adversaries and the importance of remaining undetected for the duration of extended tactical operations.

B. EFFECTIVENESS THROUGHOUT HISTORY

1. Battle of Trafalgar

Admiral Horatio Nelson was able to make history by utilizing his communications skills and training to ensure that his fleet of ships worked together in order to achieve success. This combination of skill and communication culminated with him leading the Royal Navy to a victory at the Battle of Trafalgar. Nelson used flag hoist communications to perfection by signaling the British fleet to form into two columns to approach the French fleet although the flag hoist signals were important, the success of Admiral Nelson and his ships was not only due to the effective signaling demonstrated. "Of paramount importance, Nelson had done what Brueys had not; he had spent his two months at sea not merely drilling his force but discussing and planning the battle," (Hughes, 2000). It took months and even years of meetings with his Officers and crews in order to ensure that his concept of operations was fully understood by all parties. Throughout the battle, Nelson maintained control of the ships under his command by visually communicating his orders and intent. Nelson only sent two signals via flag hoist throughout the entire engagement which illustrates the effectiveness of his communication (Pope, 1999). Nelson's visual communications skills and expertise allowed for the British fleet to maintain organization and ultimately emerge as the victors in this battle.

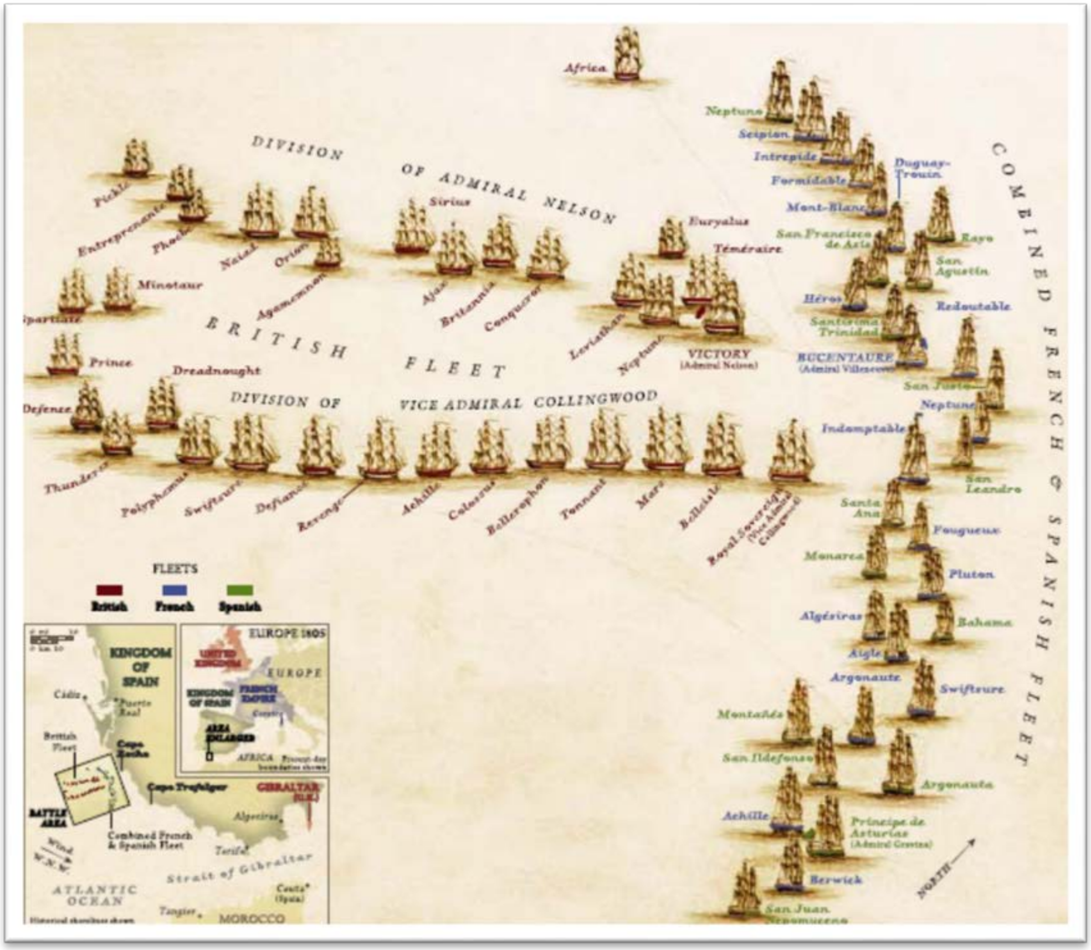

Figure 2. Admiral Nelson’s formation at the Battle of Trafalgar (From Lyon, 1996).

2. World War II

The most common type of visual communications used during World War II battles was the flashing light method. Flag semaphore and flag hoist were used as well, but with the advent of radio communications and the convenience associated with voice communications caused traditional, visual methods of communication were used less as time progressed. In the event that radio communications were destroyed due to the nature of the war, visual communications were used in their place and were effective, especially given the fact that Allied forces all knew and understood Morse code, the primary foundation for flashing light communications. Visual communications methods were not only used at sea, but also in land battles. Flares were lit to inform units of their positions and flashing light was used in order to communicate instructions and orders from sea to land based units.

C. PRESENT-DAY COMMUNICATIONS

Today, the Fleet relies heavily upon radio and voice communications and rarely uses any sort of visual communications method. Flag semaphore, flashing light, and flag hoist are only used in specific ways and proficiency with these methods is lacking. Flag hoist communications are generally used to express an explicit message such as “I am coming alongside” or “Commence refueling” or to relay a continuous short message while in port such as “There are Personnel Working Aloft” or “There are Divers Over the Side.” Flag semaphore is rarely used for anything in the present day and when used, it is primarily to send messages between ships for underway replenishment or to guide helicopters to safe landings on flight decks of smaller vessels. Flashing light is the least used of the three methods mentioned as the Morse code and techniques are no longer required to be taught, and many ships are not equipped with the required equipment to execute the communication method.

D. JUSTIFICATION FOR VISUAL COMMUNICATIONS

Visual communications need to be a point of emphasis moving forward into the future. The Fleet and the military in general have gotten away from being proficient with and utilizing visual communications in favor of voice communications, but threats exist today that render voice communications inoperable, which requires proficiency and an understanding of how to send and receive signals visually. For instance, voice communications are much more susceptible to jamming and interception. In an A2AD environment, when adversaries are attempting to deny the use of the electromagnetic spectrum, the use of visual communications is imperative because electronic signature needs to be reduced in order to avoid detection by adversaries.

Foreign navies are much more proficient and practice visual communications much more often, so when operating with foreign ships, it is vital that the Fleet know the procedures and proper way to operate visual communications equipment such as flag hoist, flag semaphore and flashing light. Visual communication techniques allow for a more discrete and essentially jam free method of communication in an emissions controlled or restricted environment, which will certainly be seen more often now and in the future.

E. VISUAL COMMUNICATIONS METHODS

1. Flag Semaphore

"Semaphore is used in the fleet primarily for dispatch work. It is the most rapid means of daylight communication for this purpose and its use is universal," (Lewis, 1928). The most prominent type of flag semaphore used throughout the history of the Navy is that of two flag semaphore. The two flags are square in shape and signals are encoded based on the position that the flags are held and waved. Flags are colored differently for sea based and land based communications.

Figure 3. An illustration of the flag semaphore method of visual communication (From Martin, 2012).

Sea based communication flags are red and yellow, while the land based flags are white and blue. Five motions are used by the signaler in order to send messages. The flags can be moved to the left, moved to the vertical position, moving the flags to the right, back to vertical position, and then dipping the flags. Moving the flags in different combinations of directions sends the message. Different angles the flags are displayed at also translate to different meanings. The flags are generally fifteen inches square and are mounted on twenty-two inch long staffs.

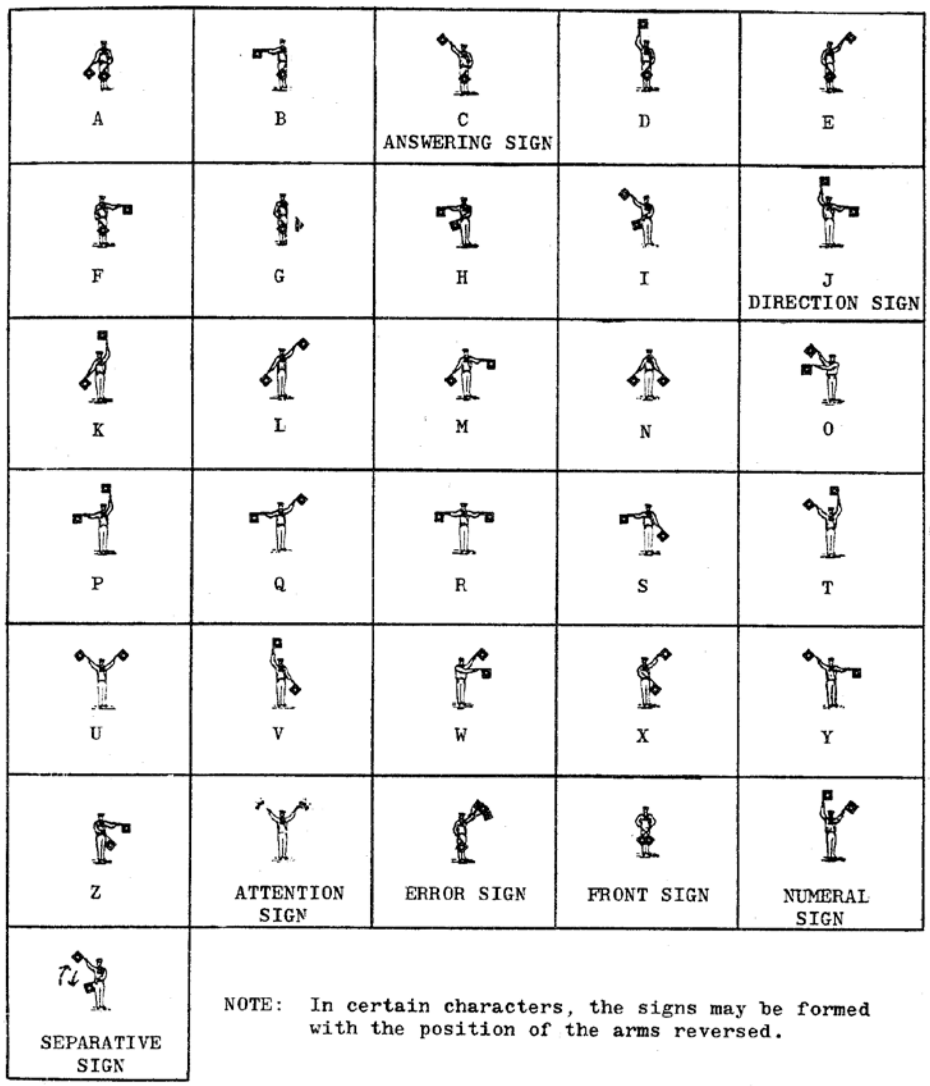

Figure 4. A chart of the Semaphore characters (From Communications Instructions Signaling Procedures in the Visual Medium, 2005).

a. Present-day uses

Flag semaphore is rarely utilized in the Fleet as a regular communications method, except for a few specific evolutions. This method is no longer taught to young sailors and is, for all intents and purposes, a lost art. Flag semaphore can still be utilized in specific instances, such as providing quick and efficient visual communications between ships during Underway Replenishment. For UNREP, signals are passed back and forth from the refueling stations in order to ensure the operation is conducted smoothly and safely. Other uses of flag semaphore include flight deck operations for smaller ships operating with a helicopter or well deck operations on an amphibious ship when launching and recovering amphibious assault vehicles. Signals are sent to the helicopter from the flight deck instructing it to land or wave off the landing. Flag Semaphore should be used more than it is now, because of its simplicity and effectiveness. This form of communication allows naval vessels to conduct special evolutions efficiently during times of increased emissions restrictions.

b. Advantages of flag semaphore

Flag semaphore is best used when ships are within a couple thousand yards of one another and a clear line-of-sight is available. In addition, no electromagnetic energy is required to be emitted in order to execute the transmission and receipt of a message, which ensures that flag semaphore is an effective method of communicating in an EMCON or HERO environment. The range can be extended if there are binoculars available to see the flags and what signals are being passed from the sender. Flag semaphore is a quick and efficient method of communicating short messages between two ships. While executing an event such as an underway replenishment or helicopter operations, where clear and concise communications are required to ensure the evolution runs smoothly, flag semaphore works perfectly. The components needed to execute flag semaphore are kept to a bare minimum. All it requires are two sailors and flags in order to communicate the messages and intents of each ship and because the messages are relatively simple and short, the risk of confusion is minimized. Flag semaphore is effective for launching and recovering amphibious assault vehicles from a ship due to its simplicity and the fact that the proximity between signalman and the vehicle is close, so there is no risk of losing the signal through any visual obstruction. This form of communication makes launching, recovering, and moving amphibious assault vehicles around in the well deck an easier task if voice communications are not available because of emissions control or HERO restrictions.

c. Disadvantages of flag semaphore

Flag semaphore requires the signalman to be knowledgeable in order to ensure that the proper signals are sent, which can pose an issue and leave a chance that an error in the signal can occur. Additionally, the flag semaphore technique can be slower than other techniques, depending on the length and complexity of the message being transmitted and requires the vessel receiving the message to have eyes on target at all times to ensure the full message is received as intended. Flag semaphore also requires a clear line-of-sight with no obstructions between the signaler and receiver. If there are any obstructions between the two stations communicating, then this method of communication will most likely become ineffective and difficult to execute. Flag Semaphore also requires the communicating vessels to be operating in close proximity to one another due to the fact that the flags are much smaller than the ones used for Flag Hoist Communications. A feasible distance that which flag semaphore can be transmitted and received is less than a mile, unless some sort of device such as binoculars are in use by the receiving unit.

2. Flag Hoist

Figure 5 provides an illustration of the flag hoist method of visual communication. In Figure 5, Sailors are conducting a flag hoist exercise, which is important in maintaining proficiency in this important skill.

Figure 5. Sailors conducting a flag hoist exercise conducted in the Seventh Fleet Area of Operations (From the U.S. Seventh Fleet website, 15APR2013).

a. Flag hoist description

The French developed flag hoist systems in the latter part of the eighteenth century and were meant to provide ships with a quick, simple, and effective method of communication. These flags all had specific meanings that were predetermined and allowed ships to communicate with one another while at sea or in port. Flag signaling allowed ships to maneuver tactically together and communicate other types of important signals. The flags also have different meanings based on where they are hoisted on the mast and how they are oriented with one another.

Flags used for flag hoist communications come in four different shapes; rectangular, rectangular with a triangular cut in the outboard edge, a smaller triangular shape, and a slightly longer triangular that comes to a point (usually termed “pennant”). Flags used also have different patterns and color combinations in order to provide a more simple and effective method of distinguishing the flags from one another (Sterling, 2008). The shapes and colors of the flags remain largely unchanged today and because of this, most nations using this form of communication have a common understanding of the meanings of flag hoist signals. Flag hoist signals are most often used to convey a single message or code, and change infrequently. This type of visual signaling is done by raising and lowering individual flags, one at a time. The flags are used to convey messages to another unit. Flags must be retrieved from a storage bin, unfolded, attached to the halyard, and then raised. Once the message is no longer needed, the flags are then lowered, folded up, and put back into the storage area. The raising and lowering of these flags is a long and tedious process.

b. Key historical uses

Admiral Horatio Nelson used flag hoist communications heavily during the battle of Trafalgar as well as previous battles in which Admiral Nelson was a part of. It was the simplest and most effective way to communicate commands to other ships in his battle groups. As previously stated, Admiral Nelson only needed to communicate two separate flag hoist signals during the battle of Trafalgar in order to guide his British fleet to a victory (Lyon, 1996). The fact that only two signals were required shows that while flag hoist communications is simple, it can be extremely effective if executed properly. Throughout his naval career, Admiral Nelson continued to use flag hoist communications and was able to demonstrate its effectiveness in both peacetime steaming and war time steaming.

c. Present-day uses

Today, flag hoist communications are rarely used for tactical communications as most tactical signals are transmitted and received through line-of-sight voice methods. Flag hoist has become obsolete in terms of tactical communications but is still used by ships in port and a few cases underway to convey intentions of the vessel or an operation that the vessel is engaged in. Examples of these are underway replenishment and helicopter operations underway and personnel working aloft, refueling, moving ammunition, and personnel working over the side in port.

Flag hoist communications are more often used to convey a simple message to other vessels in the surrounding areas, but they are not generally used in tactical maneuvering situations or combat operations. Flag hoist exercises are conducted while ships are in port to ensure that ships can at least transmit and receive simple signals. Flag hoist communications are not used for executing turns and speed changes while steaming in formation like they once were. These signals are now sent and received via voice communications methods, which can cause delay in reaction due to the time it takes to decode the message, and in a worst case scenario can result in collision at sea.

d. Advantages of flag hoist

Flag hoist communications are advantageous because they are pre-determined messages for each flag hoisted and are simple for other ships to distinguish as long as visibility is clear. Flags also have the ability to stay hoisted for a period of time so that a message can be in effect for as long as it is required. Flag hoists are also used to signal formation changes when ships are steaming in formation and require maneuvers to be performed simultaneously. This type of communication allows for quick and effective communications between ships in formation and as long as visibility is clear, there is limited confusion. Flag hoist communications have been common practice throughout naval history until recently because of the development of voice communication. This fact indicates a distinct advantage associated with flag hoist because it is widely known and understood, which means it can be an effective method of visually communicating with foreign ships and foreign navies in a time of war.

e. Disadvantages of flag hoist

The flag hoist method of communication is at a distinct disadvantage when compared to other methods of communications such as VHF and UHF line-of-sight because the vessel sending the signal is limited in what can be transmitted. Shorter, pre-prepared signals are the only feasible type of signals that can be sent whereas with voice communications and other visual methods, longer, more precise messages can be transmitted. In addition to short length messages and the lack of ability to send specific and detailed messages, flag hoist communication is also susceptible to color confusion and a lack of wind which could make it more difficult to determine what flag is hoisted (Sterling, 2008). Additionally, because flag hoist is so widely understood and widely used around the world, adversaries might easily be able to decipher what messages were being transmitted if they were within line-of-sight of the sender and receiver. This method of communication is also susceptible to LOS obstructions or changing ship orientation. In instances where thick fog, high sea state or poor weather is present, signals are much more difficult to transmit and receive.

3. Flashing Light

a. Flashing light description

Morse code was developed primarily by the telegraph inventor Samuel F.B. Morse in 1843. Morse code is essentially numbers and letters represented by short and long sounds. Morse code is usable via many different methods to include telegraph, sound, and flashing lights. Flashing light communication was derived from Morse code, as the signals are similar and can be easily translated. The United States Navy adopted the English Morse Code for signaling in 1876, but in 1905 moved away from English Morse Code and transitioned to the Continental Morse Code. "Flashing lights are primarily used by the fleet when the ships are darkened and it becomes necessary to disclose the presence of the fleet or the location of the ships in it," (Lewis, 1928). Flashing light is mostly utilized as a short distance/line-of-sight type of communication at dark or in low light situations. Flashing light communications started out utilizing lanterns which required fuel, but by 1916 the Navy started using the arc-signal searchlight which had a quick-closing, venetian-blind shutter, which allowed signals to be sent quicker and more efficiently. Although messages are able to be transmitted quickly, decoding the messages can be difficult. Figure 6 illustrates how the Navy sends Morse code signals via the flashing light technique.

Figure 6. Sailor sending a Morse code signal via the flashing light technique (From the U.S. Seventh Fleet website, 22APR2013).

b. Key historical uses

One of the most well-known uses of Morse code throughout history has been the story from the battleship Oklahoma shortly after the attacks by the Japanese on the United States Fleet at Pearl Harbor in 1941. Sailors trapped in the capsized vessel that fateful day were able to utilize Morse code by tapping on the hull of the vessel indicating the number of sailors who were still alive and needed evacuation. Sailors on the outside were able to maintain communications with the sailors trapped inside the ship by tapping on the hull. This type of communications was vital in saving as many as three-hundred sailors that day and was the platform for flashing light communications, so these sailors were proficient with it.

A quote from *Military Communications; From Ancient Times to the 21st Century* sums up the importance of this method of communicating. “Almost every signalman or radioman in the U.S. Navy learned how to send and receive Morse by sound over a telegraph line or radio, a tap on the ship’s hull, or by flashing light visible day or night,” (Sterling, 2008). The proficiency demonstrated in this instance is not the same for most of today's sailors in the Navy, which is why there is a growing need to acquire and become proficient at a visual communications method such as QR codes for communications.

c. Present-day uses

As previously stated, the use of flashing light and Morse code has fallen off significantly with the advent of new technology and is not generally used prominently in the Fleet. Many ships in the fleet today do not have functioning equipment in order to send signals via the flashing light method, and only ensure that the equipment can pass materiel inspection every couple of years. Training sailors in this method of communication is generally left to each individual ship, but it typically does not receive the necessary training attention because it is too time consuming. Additionally, training sailors prior to arriving at the ship is also too expensive and is not feasible. Even for the ships that do have functioning equipment, this type of communication is still rarely utilized, except for the occasional training exercise between ships. Many other countries are much more proficient with Flashing Light and Morse code, which makes it important for the Fleet to understand in order to effectively communicate with other NATO ships in an A2AD or emissions restricted/controlled environment.

d. Advantages of flashing light

In 1958, Colonel Charles W. Gibbs stated that the trend for the future was away from voice communication and towards visual communications because visual signals are much faster and more accurate than audible signals. In addition, he argued, "the human voice is too slow for the millisecond environment of the modern missile" (Woods, 1965). Accuracy and timeliness are two important qualities to have with regard to tactical communications and are two distinct advantages of the flashing light communications system. Additionally, flashing light communications are used across the globe by foreign Navy's, which allows for a communications system that can be used when operating with ships from other countries. Morse code has been practiced and comprehended for many hundreds of years, which makes provides the flashing light technique with this distinct advantage. Flashing light cannot be jammed because no RF energy is emitted through this technique. The only way a flashing light message can be intercepted is if the adversary is within line-of-sight and has a clear view of the message being transmitted by the sending unit. Although flashing light communications are normally limited to line-of-sight, it is believed that these transmissions can be bounced off clouds at night in order to achieve a longer range.

e. Disadvantages of flashing light

The flashing light communications system is limited by the human eye's ability to detect it. If the receiving vessel or station is not able to locate the signal due to distance or any line-of-sight obstruction, then the signal will not be received. Additionally, if some portion of the signal is received, but another portion is missed, then the advantage of delivering a timely signal is lost because the signal will need to be retransmitted which might prove costly in a tactical environment. In reference to the line-of-sight obstructions being a disadvantage, "If the weather is a thick dense fog or pelting rain it might stop it," (Woods, 1965). Although this statement is accurate, there are stories of ships in World War II communicating with flashing light in extended ranges by bouncing the light off of clouds in order to reach farther distances. It was previously stated that flashing light and Morse code were understood globally. Although this is an advantage for this communications method, it is also a distinct disadvantage. Because of this, adversaries can easily intercept and decode a message not intended for them if the enemy has a clear line-of-sight to the sender and receiver.

F. CHAPTER SUMMARY

Throughout the duration of its use, flag semaphore has proven to be an effective visual communications method for the United States Navy. It requires little equipment, a small amount of manpower, and a basic knowledge of the signals in order to execute it properly. This method has provided assistance in landing helicopters on flight decks, and successfully refueling ships at sea for many years, all without having ever having to emit any RF energy. This method of communication is simple and effective, has been used when conducting a variety of shipboard operations for many years, and allows the vessels operating together to remain radio silent and stay undetected by the adversary.

Flag hoist communication was once prominent and proved to be an extremely effective method of communication in battles such as The Battle of Trafalgar, when Admiral Nelson transmitted essential messages to his subordinates in order to ensure victory. Although it is not used as much underway as it once was, Flag Hoist Communications has a place in the Fleet to be used during special evolutions and by ships in port to transmit multiple continuous, short messages at one time. Although an advantage to Flag Hoist is that it requires zero RF emissions to be effective, there are also downsides to the method mentioned in this chapter such as the restrictions of communicating only short, predetermined messages.

Flashing light communication is an effective method of visual communication when it is understood fully. Its wide field of view allows ships to be stationed at wider angles off of the transmitting ship and still be able to receive the message. Unfortunately, Flashing Light is yet another example of an effective visual communication method that has been forgotten by the United States Navy and other branches of the military because of newer communication technologies. Other countries remain proficient and stress the importance of it, while the United States relies heavily upon voice communications to transmit and receive messages, which might eventually place the United States military at a distinct disadvantage when operating in an Anti-Access Area Denial situation or an emissions restricted environment.

IV. RF LINE-OF-SIGHT (LOS) COMMUNICATIONS OVERVIEW

A. CHAPTER OVERVIEW

This chapter briefly describes the High Frequency (HF) Line-of-Sight, Very High Frequency (VHF) Line-of-Sight and Ultra High Frequency (UHF) Line-of-Sight communications methods. It provides a general description of HF/VHF/UHF line-of-sight communications, examples of historical use, and examples of present day use, how the system functions, advantages of the HF/VHF/UHF LOS technique, and disadvantages associated with HF/VHF/UHF LOS communication. There is no doubt that HF/VHF/UHF line-of-sight offers many advantages over visual communication methods, but this does not dismiss the fact that the fleet maintains a strong necessity to be proficient with at least one visual communication method based on the emerging threats posed from other nations moving into the future. Table 1 provides a brief overview of the frequency ranges, effective ranges, wavelength ranges, and vulnerabilities associated with each RF LOS communication method.

	Frequency	Effective Range	Wavelength Range	Vulnerability
HF	3MHz-30MHz	25–50 kilometers	100 meters to 10 meters	Ionospheric effects, jamming
VHF	30MHz-300MHz	25–50 kilometers	10 meters to 1 meter	Multipath effects, jamming
UHF	300MHz-3GHz	25–50 kilometers	1 meter to 0.1 meter	Multipath effects, jamming

Table 1. Summary table providing a comparison of HF, VHF, and UHF communications.

B. HF LOS DESCRIPTION

High Frequency (HF) communications are those RF communications that occur between the frequencies of 3 MHz and 30 MHz (Kim & Muehldorf, 1995). Communications systems operating in the HF portion of the electromagnetic spectrum have the ability to operate at long distances because of the fact that the radio waves are reflected back down to Earth from the ionosphere.   HF communications can be used over distances up to 8000 km given ideal environmental conditions. The HF frequency range provides the optimal frequencies for long distance communications, without having to rely upon satellites for relay. HF communications can provide data transfer rates of up to 4800 bits per second. The HF spectrum is a limited resource, so effective use of the spectrum is especially important. HF is highly susceptible to ionospheric changes, which leads to the requirement of multiple frequencies being available for use in this spectrum.

C. VHF LOS DESCRIPTION

Very high frequency line-of-sight communications operate between 30MHz and 300MHz in the EM spectrum. VHF communications support ship-to-ship, ship-to-shore, and ship-to-air line-of-sight communications. The VHF band is attractive because line-of-sight propagation results in a low detectability and the availability of wider than usual bandwidths allows for spread spectrum application.

VHF signal propagation is not affected by ionospheric reflection and the signals travel in straight lines, but for ship-to-air communications, and vice versa, there is a multipath effect on the transmissions. Multipath effects allow this form of transmission to be less susceptible to jamming, but can also have negative effects on the transmission such as delayed receipt of the message and longer time to transmit (Kim & Muehldorf, 1995). Ship's structures can cause reflections, which can interfere with direct line-of-sight signals. Superstructures of ships can also cause multipath effects, which can often result in a weaker radio signal. VHF line-of-sight communications range is affected and limited by these effects. Figure 7 demonstrates the ability to achieve longer ranges with a taller antenna height.

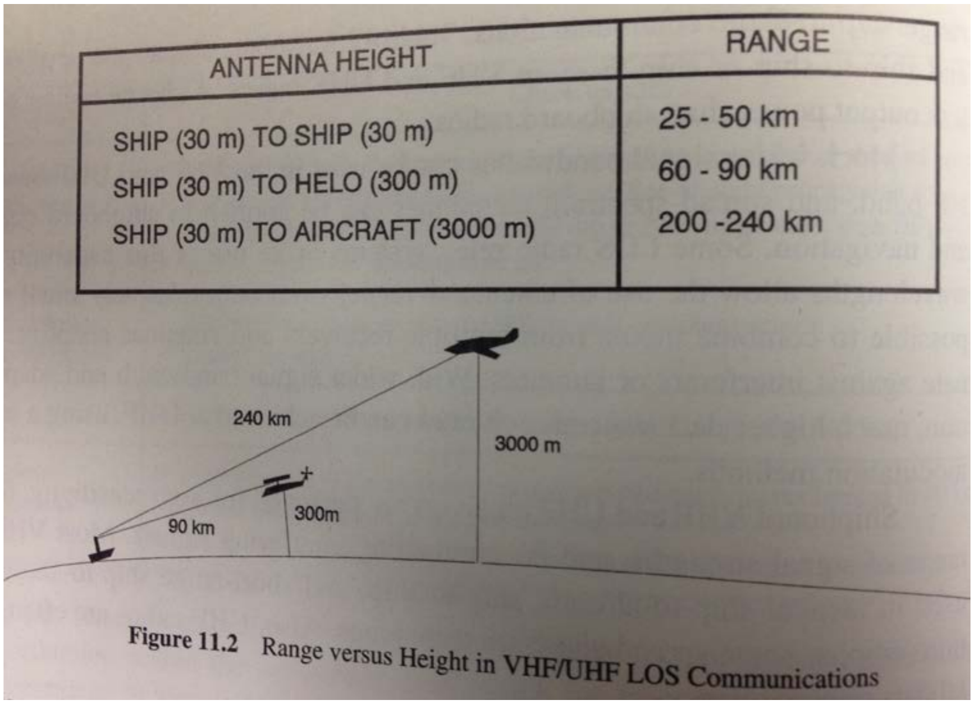

Figure 7. Range versus height chart illustrates that increased range is achievable through a taller antenna height in VHF/UHF LOS communications (From Kim & Muehldorf, 1995).

1. VHF LOS Historical Tactical Uses

VHF LOS communication came into prominence before World War II and has been in use ever since. Voice communications allowed the United States Navy to conduct various different types of raids and operate effectively in battles during World War II. This type of communication is a great supplement to visual communications, and during WWII, voice communications were not as susceptible to jamming and detection as they are today because of the limited technologies possessed by adversaries. This is not as true today as it once was because adversaries are extremely technologically advanced and can match most of our own technologies.

2. VHF LOS Present-day Uses

The most common use of VHF LOS communications in today’s environment is that of Bridge to Bridge (BTB) radio. Commercial and military vessels at sea utilize BTB communication to arrange safe passage and to identify vessels at sea. This is an important application of VHF LOS communication and without it, everyday transportation at sea is more difficult because of the reliance vessels now have on this service because of the fact that its usage is required by International Law. In addition, BTB communication is the most prominently used method when conducting Visit Board Search and Seizure and Anti-Piracy operations. VBSS missions require constant BTB communications between small boats and surface combatant. Anti-Piracy operations require that interrogations by the surface combatant to the vessel in question be conducted via BTB communication due to the fact that BTB is internationally used and understood. It is also important in the air domain as it is the primary means of communication between air traffic controller and aircraft. In other words, VHF LOS communications serves an important purpose in both the air and sea domains because it reduces the risk of collisions occurring and is an effective method for identifying vessels and aircraft that are unknown.

3. Advantages of VHF LOS Communications

VHF LOS Communications offers a plethora of advantages over visual communications. This type of communication is quick and effective when transmitting and receiving messages because the messages do not have to be encoded in any way. All that is required is to think, key, and speak to transmit the message. The receiver will be able to hear the message and understand it without having to refer to a publication or manual to decode the message because it is sent in plain voice. VHF LOS has a range of twenty-five to fifty kilometers between two ships and a longer range between ships and helicopters due to the height of the sensors being used. The range increases again when transmitting from a ship to an aircraft.

This longer range is useful because the sender and receiver do not necessarily need to be within sight of each other, as long as there is a clear path between the transmitting sensor and receiving sensor. VHF LOS communications do not require larger sensors or antennas which make it an ideal system for shipboard use because of the inherent lack of space on board a ship’s mast or superstructure for mounting antennas and other equipment required for voice communications to be effective. VHF LOS communication is less effected by interference from other electrical devices when compared to lower frequencies (Kim & Muehldorf, 1995).

4. Vulnerabilities of VHF LOS Communications

There is much vulnerability associated with VHF LOS communications. Multipath effects, ionospheric effects, the threat of being jammed, and conditions which warrant emissions control to be in effect are all examples of vulnerabilities associated with VHF LOS communications. These vulnerabilities are necessary to be addressed in order to have a better understanding of limitations associated with this type of voice communications system.

The multipath effect can have a negative impact on VHF LOS communications due to interference with other signals or reflections from a ship's structure. "When an aircraft transmits signals to a ship, the direct wave and the reflected wave interfere with each other as the two waves arrive with different phases," (Kim & Muehldorf, 1995). Multipath effects on VHF LOS communications are not avoidable and add to the vulnerabilities associated with this method of voice communications.

Ionospheric effects occur often and can interfere with radio communications. These effects are due to the ionized regions differing in ionization density and have a negative impact on the propagation of radio waves through the atmosphere. "These effects include reflection, refraction, absorption, change of polarization, scatter, and diffraction of some or all of the incident radio energy," (Little, Rayton & Roof, 1956). If these ionospheric effects are severe enough, the transmitted signal might be lost, which leads to a delay in receiving the signal if it needs to be retransmitted.

D. UHF LOS COMMUNICATIONS OVERVIEW

1. UHF LOS Description

The radio frequency spectrum that makes up UHF is between 300 MHz and 3 GHz. The effective range of UHF line-of-sight communications when being used for ship-to-ship communications is between twenty-five and fifty kilometers. The standard UHF LOS radio found on board a naval vessel is the AN/WSC-3(V)6 radio. This radio operates in the 225 MHz to 400 MHz range. The radio consists of an antenna coupler, a receiver-transmitter, and a QPSK modem (Kim & Muehldorf, 1995). In addition to this radio, the Navy's Link 4A aircraft control link also operates in the UHF spectrum. Link 16 also relies on this type of communication medium and is essential for the fleet to be able to operate effectively and efficiently. UHF LOS communications are similar to that of VHF LOS communications.

2. UHF LOS Present Day Uses

Link 16 relies heavily upon UHF LOS communications and is presently the United States Navy's most vital tactical data link to ensure combat operations and training exercises are effective. This system is vastly important to the mission of the Navy and ensures that all the units involved in a mission share a common operational picture. It is best described as a high speed, digital data link between ships, aircraft and other units. UHF line-of-sight communications are the backbone of the naval fleet, but in situations that require emissions control to be in place, many of the systems operating in the UHF spectrum are secured, which can inhibit the operational effectiveness of vessels at sea. For this reason, a reliable and effective visual communication method is needed (Kim & Muehldorf, 1995).

3. Advantages of UHF LOS Communications

UHF LOS communications are more difficult to jam over the traditional HF band because of the ability to use spread spectrum techniques. "With wider signal bandwidth and adaptive equalization, much higher data transmission rates can be achieved at UHF, using a wide variety of modulation methods," (Kim & Muehldorf, 1995). The spread spectrum capability allows for the system to combat interferers and jammers to some degree. UHF line-of-sight communications systems do not require large antennas, which make it suitable for use on board ships because of the natural lack of space available. This type of LOS voice communications is quick and simple to execute if all of the equipment functions properly as intended. In addition, UHF LOS communication allows for a much higher data rate than other lower frequency communication systems.

4. Vulnerabilities of UHF LOS Communications

Although UHF line-of-sight communications are effective and efficient, there are a few vulnerabilities associated with this type of communications that need to be addressed. UHF LOS communications cannot be used during some instances when certain Emissions Control parameters are in effect, which essentially renders the UHF band inoperable for the time period that EMCON remains in effect. Additionally, the UHF band is susceptible to jamming, which can also render it inoperable. These limitations make it all the more necessary for a visual method of communicating tactically between naval units at sea.

UHF LOS communications suffer from multipath effects that can weaken the signal and due to the small wavelength associated with UHF signals; a ship's superstructure can interfere with the signal and cause reflections which can also weaken the signal. Another drawback associated with UHF LOS communications is that there is a significant range limitation. In order to expand the range of UHF communications, the use of aircraft and unmanned aerial vehicles is required.

E. CHAPTER SUMMARY

While VHF/UHF LOS communications offers the Fleet and the tactical user many advantages over other forms of voice communications and visual communications, it is still susceptible to jamming and detection by the adversary. It provides users with unique capabilities such as Link 16, but is also prone to multipath effects and ionospheric effects, which can affect the clarity and timeliness of the signal. In an emissions restricted or Anti-Access Area Denial (A2AD) environment, VHF/UHF LOS communications can be much less effective, due to its electromagnetic transmissions, further stressing the need for a reliable visual communication method. With the possible advent of a new visual communications method such as QR code communications; the significance of these effects can be greatly reduced.

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V. ONE-DIMENSIONAL (1D) BAR CODES, TWO-DIMENSIONAL (2D) BAR CODES, AND QR CODES

A. CHAPTER OVERVIEW

Over time, one-dimensional bar codes evolved into two-dimensional barcodes, which then led to the creation of quick response codes. QR codes were ultimately developed due to the fact that there was a growing need to be able to more effectively track inventory and the requirement to have the ability to store more and more data within these barcodes was growing. This chapter discusses the many features of QR codes that allow them to be effective for visual communications.

B. HISTORY OF BAR CODES AND QR CODES

Bar codes have been used for many years and are versatile in their use. They are limited though in their data capacity and tend to require larger displays to be read reliably. Originally developed for cataloging railroad cars in the 1960s, one-dimensional barcodes were not commercially prolific until they were used to automate retail checkout systems in the mid-1970s. In the years to follow, the Universal Product Code (UPC) format became the standard method for representing products throughout the retail industry (Fox, 2011).

A QR code is a two dimensional bar code designed to work similarly to a once dimensional bar code but with significantly more data capability. QR codes were originally developed for Denso Corporation in 1994 (Kieseberg et al., 2010). Ultimately, these QR codes were a solution to the growing need for the ability to effectively track inventory in the automotive manufacturing industry and to have the ability to store larger amounts of data within the barcodes themselves. QR codes have been approved as AIM, JIS and ISO standards and are fast becoming a mainstream technology (Sutheebanjard & Premchaiswad, 2010). Aside from QR codes, other examples of two dimensional matrix codes are Aztec, DataMatrix, Code One, Semacode, SPARQ, MicroQR and MaxiCode. Similarly, two dimensional bar codes can exist as stacked one dimensional bar codes such as PDF417 and Code 16K.

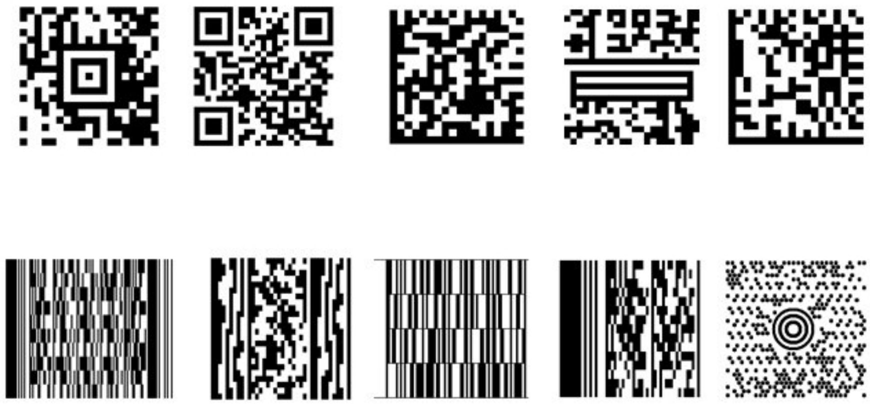


Figure 8. Side by side comparison of commonly used 2D barcodes, to include matrix and stacked bar code styles.

A common use for QR codes is to conveniently provide mobile phone users with URLs to promote websites and advertisements. As evidence to the increasing use of QR codes, URL shortening services such as Goo.gl and Bit.ly now exist. Additionally, there are countless web-based services that can be used to generate and read QR codes.

C. CHARACTERISTICS AND GENERATION OF QR CODES

The details provided in these sections provide a simple overview of the key characteristics of QR codes. The Wikipedia article on QR codes (http://en.wikipedia.org/wiki/QR_Code) is a primary resource necessary for understanding the potential capabilities and design choices presented in this work. It is provided as a ready reference in Appendix D.

A QR code is a two-dimensional binary representation of data structured using black and white patterns. The represented data can consist of numeric, alphanumeric, binary and kanji characters. Since a two-dimensional code adds data in the vertical direction as well as the traditional horizontal direction of a one-dimensional barcode, it is capable of representing magnitudes greater of data.

Figure 9. General characteristics of a 2D QR code compared to a 1D traditional barcode (From Sutheebanjard & Premchaiswad, 2010).

The patterns are comprised of black QR bits overlayed on a field of white. Each black QR bit represents a binary 1 while the white spaces or the absence of a bit represents a binary 0. Three finder patters that look like a square bullseye are located at the corners with timing bits located between each. Because the finder patterns are always present and in the same configuration, a QR code can be detected and decoded regardless of its orientation within the plane. An added benefit of the three finder patterns is identification of the QR symbol in a complex background environment. An additional alignment pattern is added in QR codes version 2 and greater to assist in resolving codes with optical distortion.

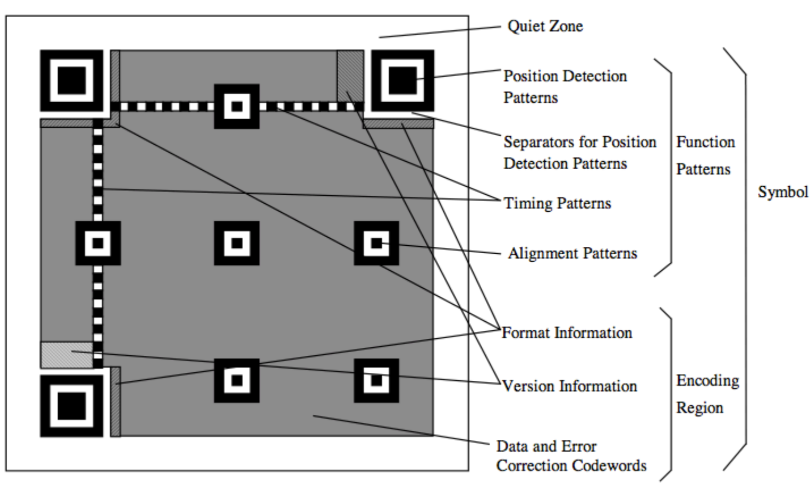


Figure 10. Key structural features of a QR code symbol (International Organization of Standards, 2006, September 01).

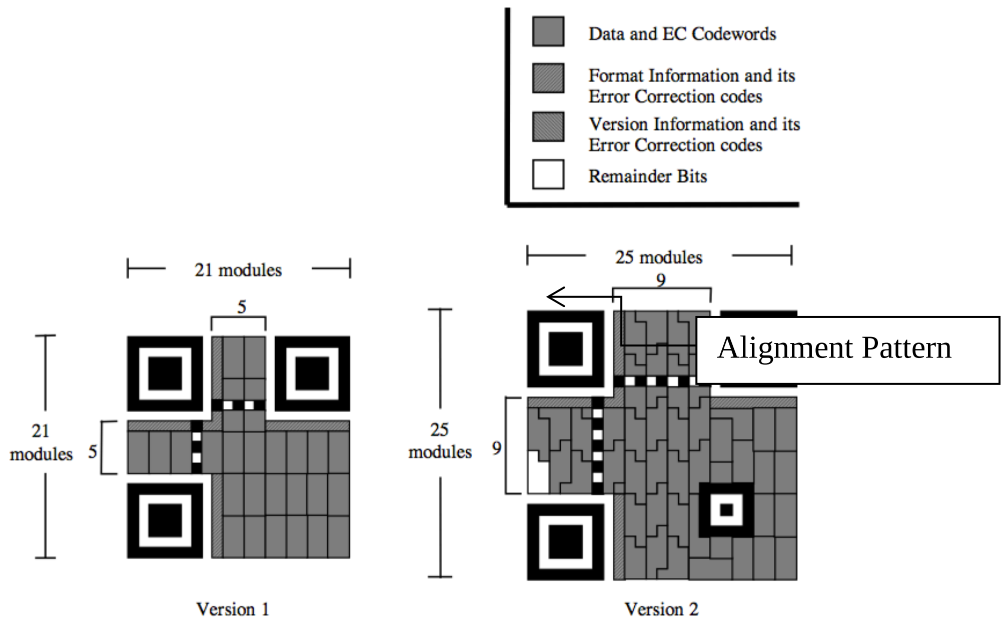


Figure 11. Comparison of version 1 and 2 QR code symbols (International Organization of Standards, 2006, September 01).

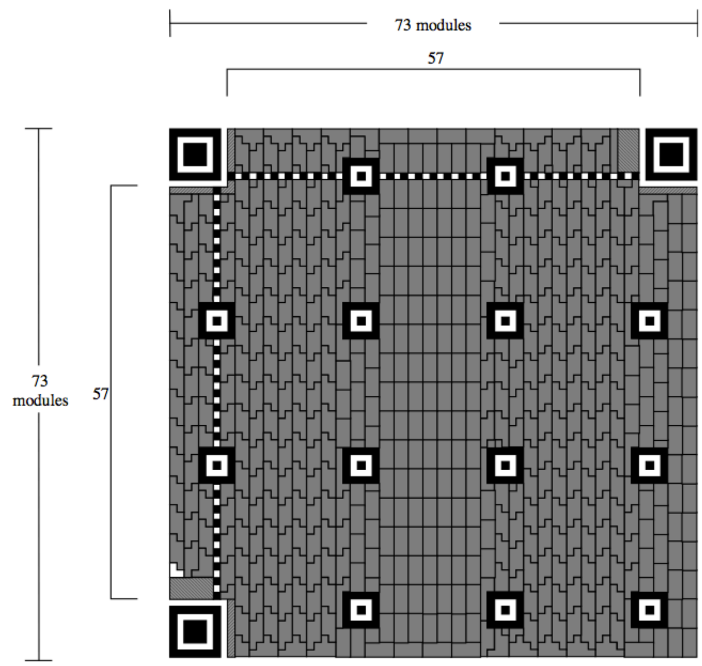


Figure 12. Characteristics of a version 14 QR code symbol (International Organization of Standards, 2006, September 01).

Inherent in every QR code is error correcting code (ECC) to compensate for misreading a QR bit or accommodating for a portion of the image missing or unreadable. Reed-Solomon error correction provides this capability, similar to nearly all other forms of 2D barcodes. The drawback of having a larger ECC is a reduced data capacity within the code. The error correction levels are as follows (Sutheebanjard & Premchaiswad, 2010):

Level	Maximum Correction Capability
L	7%
M	15%
Q	25%
H	30%

Table 2. QR code error correcting capability levels (Sutheebanjard & Premchaiswad, 2010).

Forty versions of QR codes exist each representing a unique amount of data that can be encoded and represented. Each version has a set capacity based on the available space in the code following the finder, timing and alignment patterns, and the version and format data (Sutheebanjard & Premchaiswad, 2010). A few capacity examples based on data types and a 7% ECC are shown below:

QR Code Version	Numeric Data	Alphanumeric Data	Binary Data	Kanji Symbols
1	41	25	17	10
2	77	47	32	20
3	127	77	53	32
5	255	154	106	65
10	652	395	271	167
20	2061	1246	858	528
40	7089	4296	2953	1817

Table 3. QR code capacity (International Organization of Standards, 2006, September 01).

D. READING QR CODES

QR Codes can be read from a variety of readers available on the Internet and as applications for mobile phones. In addition to these readers, there are many open source and proprietary programs that can be installed on a desktop or laptop for reading directly from files or through a webcam.

1. Mobile Devices

Nearly all modern mobile devices have the ability to scan and decode QR codes. Many free and inexpensive QR-reading mobile applications (apps) are available in the iPhone App Store and the Android Market. A few examples are NeoReader, QRReader, Scan, Quick Scan, AT&T Code Scanner, Scanner Pro, and QR Droid. A few mobile apps have the ability to create QR codes such as Qrafter, Quick Scan, QR Generator, and Market QR. Not all QR reading apps perform at the same level, but all do include the basic functionality required to read QR codes at a reasonably close distance.

2. Specialized Cameras

With the current mobile technology market it is not likely that a device will be developed dedicated solely to generating, reading, and processing QR codes or barcodes in general. If this capability were requested by a specific entity, such as the military, it would be reasonable to expect technology developers to easily develop such a product.

3. Software Implementations

Many websites exist that serve to assist with QR code functions. RACO (racoindustries.com) maintains a robust catalog one and two-dimensional barcode generators as does ZXing (zxing.org). Other websites, such as INVX (invx.com) offer simple and limited generators that are effective and simple to use. Some websites, such as Kaywa (kaywa.com), work only with QR codes, but provide detailed control when creating the codes.

Three common mechanisms currently exist with software applications that read QR codes. The first is to enter the URL of a page containing a QR code, and the service returns the decoded version of any QR codes found on that page. ZXing (zxing.com) and MiniQR (miniqr.com) offer this service. Second, a locally running software application may be allowed to interface with a computer's webcam to capture the image of a QR code and will return the decoded version. MiniQR uses this method. Third, and the most common, a website or software application may allow a user to upload a file containing a QR image for decoding. websites that offer this functionality are Online Barcode Reader (onlinebarcodereader.com), Patrick Wied QR (Patrick-wied.at) and QR Code Generator and Recovery (esponce.com).

E. QR CODE SECURITY CONSIDERATIONS

Before QR code communications can be seriously considered for tactical military applications, proper security matching or exceeding the capability of current communication systems must be proven. While a standards-compliant QR code contains a measure of security in its current design, current security mechanisms are not sufficient to ensure the protection of the data it will carry.

1. General Purpose Data Channel

The algorithms currently used to encode a QR code clearly prevent the data from being man-readable. These algorithms however, are derived from open-source libraries available to anybody with common Internet access. For increased security at this level, private encoding algorithms must be developed for communications among authorized users and protected from all potential adversaries.

Further security can be obtained by developing a proprietary two-dimensional (2D) barcode format similar to QR codes or by modifying the existing format. For instance, the finder patterns can be omitted and replaced by unique patterns unrecognizable by open-source QR readers. Another option is to invert all or a portion of the QR bits such that only an intended recipient knows to recognize and account for this change. This technique might be considered a simple Caeser cipher. Indeed, an important area for future work is to perform a comparative survey of all encryption methods and then consider what corresponding visual encryption techniques might be relevant.

Figure 13. An artist's rendering of a QR code reading, "http://qr.nps.edu" with the traditional finder patterns replaced by alternate patterns.

2. Encryption

Traditional methods of data encryption can also be used to add a layer of security. Once a QR code communication system is implemented, in-line encryption (ILE) devices or algorithms can be used to encrypt data before it is transformed to a QR code format. With such security in place, an intercepted and decoded QR code remains meaningless to unintended recipients.

3. Camouflage

Camouflage is a viable option for obscuring a QR code from the view of unauthorized users. If the camouflage material will be directly between the display and the recipient, however, modifications to the system must be in place. The normal visible spectrum can be replaced with infrared or ultraviolet displays in order to pass through the camouflage.

4. Obfuscation

Obfuscation may also be key to ensuring communication security with a QR code system. If a QR code is placed within a complex background, human interpretation may not detect its presence. With the appropriate finder patterns in place, only an optical scanner feeding imagery into an obfuscation-aware data processing algorithm can recognize the existence of the QR code, determine its boundaries, and extract the encoded data. Other standardized QR tools simply fail to read the image. In Figure 14, note the valid QR code identified by the finder patterns located in the center of the image.

Figure 14. As an example of obfuscation, a valid QR code reading, "http://qr.nps.edu" is placed within a complex background. The required white boundary layer is obscured, but can be regenerated from the finder references.

5. Steganography

Steganography is the practice of hiding information within a message, image or file. The difference between visual steganography and obfuscation in this context is that the message in steganography is much more difficult to "stumble" upon. In Figure 14, if an observer happens to scan the image, the hidden message will likely decode since some readers are forgiving about white border. With steganography, the hidden data is in such deliberately modified format, that only the recipient will know to expect it and know how to extract.

An example of information steganography is the use of intentional error bits in a series of QR codes to build a hidden data set. Most QR readers dismiss error bits and produce only the decoded message. Following successful message receipt, however, it is possible to deliberately construct a secondary message, from the decoded text and then produce a list of erroneous QR bits by comparing the two images. Reconstruction of data can then occur by using the error bits such that when all of these error bits are combined, they decode to a separate message. For example, a 1 might be deliberately changing a white QR bit to black, and a 0 might be changing a black QR bit to white. Other variations are possible based on spatial or numeric locations in the image. Of note is that separate encryption schemes can be used for these hidden messages.

6. Vulnerabilities

URL shortening services (e.g., http//bitly.com) are enticing to allow a user to encode lengthy web addresses into small QR codes. Unless this shortening is performed by a known reliable and trusted source, increased vulnerabilities are increased into the system. A nefarious third party can use these services to implement malicious code through shortened URLs.

F. QR CODES FOR TACTICAL COMMUNICATIONS

1. Advantages

Arguably the most significant advantage of QR code LOS communications is the fact that they can be conducted without emitting energy in the RF spectrum. In an emissions controlled (EMCON) environment, this will provide a critical ability to communicate between ships without increasing the possibility of position detection.

This form of communication also revitalizes historical means for LOS communications such as flag semaphore of blinking light. This capability will be imperative in a communications-denied anti-access area denial (A2AD) environment.

QR codes are easily generated, easily read, and are very simple to use, therefore they are much easier to support with common and available technology. Thus, the infrastructure for deployment ashore or within a ship is already available and in place. This ready availability also reduces the need for extensive training of personnel using the technology.

A significant characteristic of QR codes is the ability to encode large amounts of data within one QR image. This allows for lengthy messages to be communicated through a QR code, which greatly reduces the time required to decode the message compared to the traditional ways of encoding and transmitting a tactical signal. A QR code is capable of containing a maximum of up to 4,296 characters if the message is alphanumeric, which is more than enough for any tactical signal. If a series of QR codes are transmitted and coupled, this opens a significantly sized data stream between two users.

Quick response (QR) codes are also capable of storing data in both the horizontal and vertical directions, making them an ideal platform to create and transmit messages in a timely fashion.

Because QR codes are largely unidirectional and short-range, the area in which an adversary must be stationed to detect a QR code transmission is small. This creates a significantly low probability of detection (LPD) and in turn low probabilities of interception and exploitation (LPI/LPE). As discussed above, multiple options for encrypting QR codes provide an elevated level of security against any adversary.

Beyond those reasons stated here, there are many other advantages for the use of QR codes for communications. As QR code supporting and leveraging technology continues to evolve, many other advantages will emerge that have yet to be used or discovered.

2. Disadvantages

Although the use of QR code technology as digital semaphore provides many advantages, it is also necessary to mention possible associated disadvantages associated with this type of communication.

The proper environment is essential to the success of QR communications. Sufficient lighting required to capture a QR code and have the ability to decode it is important to ensure the proper contrast between QR bits for decoding. The different types of QR code readers may react differently to changes in lighting, which can pose an issue for transmitting these signals at night or in low light situations. In a shipboard environment, where this type of communications is ultimately desired, other issues such as sea state, extreme reflections from the sun, the presence of fog or sea spray and the various different angles at which ships operate in reference to one another can all contribute to communication failures.

Angular performance must be studied in order to determine acceptable maximum angles at which QR codes can be successfully read and decoded using various sensors. It is likely that ship movements from high seas and ship positioning will all affect the angle at which a QR display is presented significantly enough to reduce the reliability of the communication channel.

With current technology, range performance for QR codes is still poor. This limits the use of QR communications to very close quarters. In a maritime environment, operations in close proximity come with significant risk and are only performed when necessary (i.e., replenishment at sea).

In the case when an adversary is located in close proximity and near perpendicular to a QR code display, the possibility of detection, interception and exploitation of the signal is elevated. Current QR code reading technology is readily available to the public and many QR reading solutions are free to smart phone users. If encryption of the QR code is weak or absent, an adversary positioned as such can easily intercept and decode the communications. In addition, an adversary can effectively jam these communications by establishing a smoke screen in the vicinity of the transmitting platform.

As technology matures, it is likely that many of these disadvantages can be overcome. It is also likely that disadvantages that have not been considered or do not yet exist will emerge.

G. CHAPTER SUMMARY

Quick response codes are capable of storing more data than one or two-dimensional horizontal bar codes in a much smaller space. Multiple versions of QR codes allow for varying amounts of data to be encoded based upon the situation. QR codes are omnidirectional, which means that they are capable of being read at any orientation. For all these reasons, using QR codes for communications is feasible, provided that an uninhibited line-of-sight exists and each unit is equipped with the proper equipment.

VI. EMISSION RESTRICTIONS

A. CHAPTER OVERVIEW

Emissions control is necessary to be in place for naval vessels and can often require full radio silence for a period of time. This has major implications for voice communications and tactical capabilities, which can be augmented by a visual communications system. During radio silence, the vessel will not be able to stay in communication with the command station or other vessels operating in the area, which clearly hampers the tactical abilities and effectiveness of the vessel. This chapter discusses Emissions Control, the different levels of EMCON, and situations in which EMCON may be required of a vessel at sea. In addition to discussing emissions control, this chapter will also describe Hazards of Electromagnetic Radiation to Ordnance and the impact that HERO has on RF LOS communications.

B. EMISSIONS CONTROL (EMCON)

1. EMCON Description

Naval Telecommunications Procedures Four defines emissions control as follows: "EMCON is control of all electromagnetic and acoustic radiations, including communications, radar, EW and sonar. During its imposition, no electronic emitting device within designated bands, including personal communications devices, will be operated unless absolutely essential to the mission," (Starling, 2008). During some operations, operational requirements may require full radio silence, which means that all voice communications systems will be inoperable for that specific time period requiring EMCON, including VHF and UHF LOS communications. A reliable visual communications method can circumvent these requirements and still allow tactical units or vessels in the same Operational Area (OPAREA) to communicate effectively and efficiently. "The objectives of EMCON are to deny the enemy any way that it may locate your position, to support the efforts to disrupt the enemy's effectiveness, and to allow your actions to go unnoticed," (Starling, 2008). This fact indicates the need for a reliable visual communication method in order to allow tactical units or vessels to maintain effective and efficient command and control.

2. EMCON Levels

There are four basic levels of emissions control that vessels utilize at sea. The least restrictive level of EMCON is Delta. EMCON Delta is used during normal underway steaming and there are no emissions restrictions under level Delta, which means that the vessel is allowed to radiate any sensor that is essential to accomplishing the mission. The next level in EMCON is Charlie. EMCON level Charlie is designed to disguise the electronic signature of the vessel. Charlie allows the ship to radiate and transmit from mission-essential equipment and sensors, but it does require that sensors unique to that type of vessel be shut down in order to prevent adversaries from identifying the class of ship. EMCON level Charlie allows the ship operating in the emissions controlled environment to blend in with other vessels in the area to make it seem as though it is just like any other type of ship (Gibson, 2004).

EMCON level Bravo is more restrictive than Charlie, but still allows the ship to communicate and transfer data with other ships. Bravo further limits what is authorized to be radiated and transmitted from, but it is not the most restrictive level of EMCON. The most restrictive level of EMCON is level Alpha. EMCON level Alpha does not allow the vessel to transmit or radiate from any sensor, which means that the ship is in complete radio silence. Although the levels of EMCON are Delta through Alpha, modifications to these levels are sometimes permitted in order to allow the unit to execute mission-essential tasks (Gibson, 2004).

3. Situations that Require EMCON to be in Place

When a ship moves into a hostile environment or an environment that requires stealthy movements in order to remain undetected for a given period of time, some variation of EMCON will be put into effect. This reduces the electronic signature of the vessel and makes it more difficult for adversaries to detect. EMCON can be implemented without prior notice if it is deemed necessary for the operational environment and the safety of the units. The need to establish and maintain communications with other vessels in the vicinity or strike group and the command station on shore is still a requirement, which is what makes “Digital Semaphore” such a viable communications option for the fleet. EMCON has a negative effect on a ship’s ability to perform effective Command and Control because of the decreased communications capability that comes with emissions control in place. A reliable and effective visual communications method such as QR codes can mitigate this effect and allow the ship or ships to maintain positive communications throughout the duration of EMCON.

4. Impact of EMCON on RF LOS Communications

Clearly, the impact that EMCON has on RF LOS communications is significant. Depending on the tactical situation, ships may be required to stop radiation and transmission from all types of emitters, which clearly demonstrates the need for a visual method of communicating. RF LOS communications in the VHF and UHF ranges are effected by EMCON, which can greatly reduce the effectiveness of voice communications between ships operating in a tactical environment. EMCON conditions can completely eliminate the effectiveness of RF voice communications, increasing the importance of establishing a reliable and effective visual communications method, such as “Digital Semaphore.” Communicating tactically with QR codes will enable naval units to maintain effective command and control, even when RF emitters are secured due to emissions control measures.

C. HAZARDS OF ELECTROMAGNETIC RADIATION TO ORDINANCE (HERO)

1. HERO Description

The purpose of HERO is to prevent the accidental ignition of electrically initiated devices in ordnance, which is due to the RF electromagnetic fields (McManamon, 2008). HERO is becoming a more important issue because ordnance systems use more sensitive and lower power electronic circuits and communications and radar equipment use much higher powered gear to enable them to radiate at higher levels. HERO conditions allow for the safe movement and handling of ordnance and ammunition. The restriction imposed by ordnance that is HERO susceptible is similar to restrictions imposed during

Emissions Control. Any communications equipment that must be shut down or secured while moving or handling ammunition is labeled with a HERO warning label which indicates restrictions of that device while HERO unsafe ordnance is being handled or transferred throughout the ship.

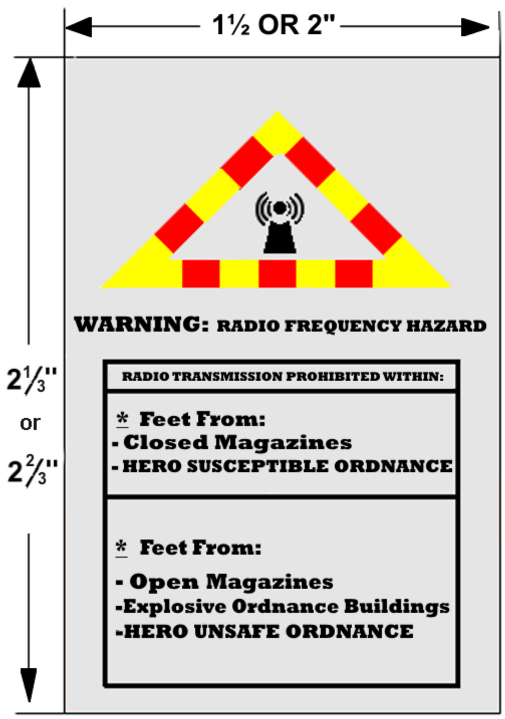


Figure 15. Example image of a HERO warning label (From McManamon, 2008).

2. HERO Classifications

There are four different classifications used to label various types of ordnance that can be found on board ships and elsewhere. The four classifications are HERO safe ordnance, HERO susceptible ordnance, HERO unsafe ordnance, and HERO unreliable ordnance (McManamon, 2008). These classifications are important to be familiar with to ensure that the correct measures are in place when moving and handling different types of ordnance. Based on the classification in place, different sensors, radars, and communications equipment must not be used in order to avoid unintentional detonation of the ordnance.

3. Situations that Require HERO Conditions to be in Place

If a ship on deployment is required to perform a missile on load or missile off load, the ship will be required to shut down certain communications systems and reduce transmissions from these sensors. Although this operation is done in port, it can still have an effect on voice communications. Other examples of situations that require HERO conditions to be employed are moving torpedoes, moving 5-inch shells, uploading and downloading Close-in Weapon System (CIWS) ammunition, and loading/unloading Super Rapid Bloom Off-Board Chaff (SRBOC) rounds. These evolutions can occur either in port or at sea, and can take a significant amount of time, depending on the quantity being moved, loaded, or unloaded and the efficiency of the personnel performing the ammunition movements. This can affect a vessel's ability to communicate effectively via voice communications with other vessels and Higher Headquarters (HHQ).

4. Impact of HERO Conditions on RF LOS Communications

HERO conditions have a significant impact on the effectiveness of RF line-of-sight communications on board ships as well as with tactical units. When HERO conditions are implemented on board ship, certain communications systems and frequencies are not to be operated due to the possibility of exploding a piece of ordnance inadvertently. Visually communicating with QR codes allow ships to be able to maintain exterior communications with other ships in the operating area while still conducting ammunition on loads, off loads and transfers. In certain extreme cases, all ships operating in a Carrier Strike Group (CSG) or Expeditionary Strike Group (ESG) might all be executing ammunition uploading/downloading simultaneously, which require these ships to be proficient at a visual communication method for the duration of the evolution in order to ensure that no ordnance is accidentally triggered or set off.

D. CHAPTER SUMMARY

Emissions Control and HERO restrictions significantly hinder a vessel's ability to communicate with other units and higher headquarters due to the fact that communications systems and certain frequency ranges must be secured. Although the purposes of HERO and EMCON differ, the impacts are similar. There are different classifications of HERO conditions and each type of ammunition falls under a specific classification with associated communications systems and emitters that must be shut down. As previously stated, there are four basic emissions control levels and each level requires different communications systems and frequency ranges to be secured (McManamon, 2008). The systems can be secured for either a set period of time if it is an exercise, or an unknown, extended period of time if the vessel's intentions are to remain unseen by adversaries in a tactical situation. Emissions Control is a hindrance to voice communications and QR codes used as visual communications can provide the Fleet with a method of still maintaining EMCON and HERO effectiveness, while possessing the ability to communicate with one another.

Emissions Control and Hazards of Electromagnetic Radiation to Ordnance both affect critical Navy war fighting and readiness capabilities. The use of optical signaling using QR codes can therefore have a major impact, due to the lack of radio frequency transmissions that occur.

VII. TACTICAL SCENARIOS FOR USING QR CODE COMMUNICATIONS

A. CHAPTER OVERVIEW

This chapter discusses various scenarios in which QR code communications may be useful in the tactical environment. It also illustrates theoretical locations for mounting different cameras required for QR code detection on ships, aircraft, UAV's and the warfighter on the ground. It will discuss all necessary infrastructure required in order for a unit or ship to have a fully operational QR code visual communications system. The most likely concept for a QR code display on board ships is that of a 360 degree rotating display. The rotating display will allow for vessels to transmit and receive messages regardless of orientation to the transmitting ship. These displays can be mounted in a variety of different locations on board the ship, depending on the ship class and space available. Angles at which QR codes are read have an effect on decoding, so it is important to provide this omnidirectional display capability. Figure 1 provides further visual explanation of the concept for tactical uses of QR codes as a visual communication method.

B. SHIP/UAV/AIRCRAFT PLATFORMS

The ultimate goal of the concept of QR code communications as digital semaphore is to employ the technology on board ships throughout the Fleet. Each class of ship has different radar requirements, mast sizes, available space for mounting new equipment, and configurations. Because of these facts, it is important to propose locations that can be ideal for mounting a QR code display on board ship. Due to the fact that QR codes as communications is a new technology being studied and experimented with, ships that will be in service for a long period of time and that are most likely to operate in a tactical environment are discussed here.

1. Littoral Combat Ship

The Littoral Combat Ship will be heavily utilized by the United States Navy in the near and distant future. Its missions will vary from Anti-Piracy operations to mine hunting operations. Because it is such a flexible platform and can perform a wide range of missions, QR codes for visual communications can be useful for this type of vessel. Due to its sleek design and small radar cross section, the LCS is an interesting prospect for this technology. The image below of the Littoral Combat Ship illustrates the sleek design of the ship. Even with this sleek design, there are many possible locations for mounting a QR code display. There are plenty of flat surfaces that can prove to be sufficient enough for the display. Ideal placement of the display can be just forward of the flight deck on the upper level. This placement allows the display to transmit messages to other ships as well as the ship's own helicopter. Figures 16 and 17 provide an idea of the area available on the forward and aft portions of the ship.

Figure 16. Littoral Combat Ship at sea, forward view (From www.militaryimages.net on 27MAR2013).

Figure 17. Littoral combat ship at sea, stern view (From www.worldaffairsboard.com on 01MAY2013).

2. Cruisers

Cruisers are often employed as Ballistic Missile Defense (BMD) capable ships and are often times designated as the Air Defense Commander for a battle group or Carrier Strike Group. They need to be able to effectively communicate with the HVU in the group in order to relay intentions and acknowledge orders given by the group commander. Since Cruisers usually operate in a group with other ships, QR code communications suit this platform nicely. There are no concerns with low radar cross section on this vessel, so there are many options for the placement of the QR code display and QR code reader. Additionally, cruisers often times deploy and operate with a helicopter squadron which leads to the need for communicating with the helicopter while it is flying. QR codes are a viable option for launching, landing, and transmitting vital information back and forth between the helicopter and the ship. As there is plenty of space available, there are many possible locations for mounting a QR code display on the fore and aft superstructures of the Ticonderoga class cruiser, which is illustrated in Figures 18 and 19.

Figure 18. Ticonderoga Class Cruiser at sea, forward view (From www.combatindex.com on 27MAR2013).

Figure 19. Ticonderoga class cruiser at sea, stern view (From www.seaforces.org on 01MAY2013).

3. Destroyers

Much like the Cruiser, Destroyers are often times deployed as BMD capable ships or deployed with a battle group or Carrier Strike Group in the operational environment. If the ship was deployed independently for a Ballistic Missile Defense mission, the importance of being able to relay messages visually is reduced, but the capability is still effective for battle group operations. Destroyers usually deploy equipped with an SH-60 helicopter or two, which presents an excellent opportunity to employ QR code communications in order to land and launch helicopters more efficiently. Much like the cruiser, there are many possible locations for mounting a QR code display on the fore and aft superstructures of the ship. Figures 20 and 21 illustrate the available surface area on board destroyers for mounting QR code displays. This placement allows visual QR code communications to take place with helicopters as well as other ships and small craft in the area.

Figure 20. Arleigh Burke Class Destroyer at sea, forward view (From www.naval-technology.com on 28MAR2013).

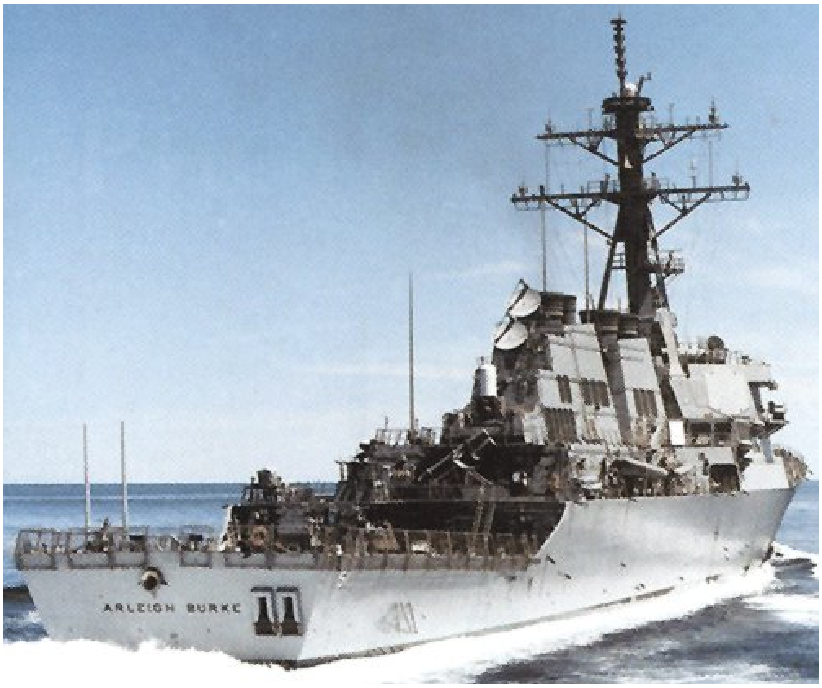


Figure 21. Arleigh Burke Class destroyer at sea, stern view (From www.naval-technology.com on 01MAY2013)

4. San Antonio Class LPD

The San Antonio Class LPD are usually deployed or operate with an Amphibious Readiness Group, so the need to be able to execute effective visual communications with other ships in the group is essential. This platform also offers a large flight deck and large, flat areas on the superstructure for mounting an omnidirectional QR code display. The LPD also presents an opportunity to employ QR codes as communications not only for flight operations, but also for well deck operations when launching and recovering LCACs and other amphibious vehicles. Additionally, the San Antonio Class LPD often times deploy and operate with a helicopter squadron which leads to the need for communicating with the helicopter while it is flying. QR codes can be a viable option for launching, landing, and transmitting vital information back and forth between the helicopter and the ship. Figures 22 and 23 illustrate the space available on board the San Antonio Class LPD for mounting a QR code display in both the forward and aft locations.

Figure 22. San Antonio Class LPD at sea (From www.san-antonio.navy.mil on 28MAR2013).

Figure 23. San Antonio Class LPD at sea, stern view (From www.globalsecurity.org on 01MAY2013).

C. TACTICAL UNITS

There are many possible applications of QR codes as a viable communications method for embedded tactical units. QR codes might be displayed on vehicles and equipment in order to identify what it is and who it belongs to. In addition, signals can be transmitted between a tactical unit on the beach and an unmanned aerial vehicle in order to relay messages back and forth between the unit and a vessel at sea or an aircraft. QR codes can prove to be important when tactical units require Naval Surface Fire Support from ships at sea. Signals can be transmitted to either a UAV, submarine, or surface ship.

D. AIRCRAFT

In addition to being a viable option for launching and recovering helicopters from a ship, there are numerous ways aircraft can benefit from QR codes being used as communications. QR codes can be painted on the runway and air traffic control towers in order to convey vital information to aircraft. Aircraft equipped with the proper cameras and other supporting equipment theoretically have the ability to decode messages from QR codes on the ground and relay the necessary information to other units requiring it to maintain a common operational picture. This might be relevant to both fixed winged and rotary aircraft, whether it be a fighter jet operating from an aircraft carrier or a helicopter operating with a smaller surface combatant. A viable application of QR codes on aircraft can be for the aircraft to be equipped with a camera with enough resolution to be able to take a picture of QR codes on the runway or control tower. These images can then be transmitted from the camera to a Personal Digital Assistant (PDA) inside the aircraft, which decode and display the message the pilot. This sort of application reduces the need to crowd frequencies used by airports and aircraft around the world.

1. SH-60

The SH-60 helicopter is the primary aircraft embarked on board the aforementioned ships. Some ships deploy and operate with two helicopters, while other smaller platforms operate with one. These helicopters are capable of performing a variety of missions, ranging from anti-submarine operations to over-the-horizon (OTH) targeting for surface ships. They also play a vital role in search and rescue (SAR) and VBSS operations. QR code communications can allow the helicopter to maintain open communication with the surface ship while conducting these missions, even if operating in an emissions controlled environment. In situations where RF energy is not to be emitted, the helicopter is able to hover near or fly by the surface vessel, capture the QR code being displayed from the ship, decode it on board the helicopter, and continue on with the mission. QR codes also provide a method for launching and recovering these assets, as well as refueling, while maintaining radio silence.

Figure 24. SH-60 helicopter landing on the flight deck of a surface ship (From www.military-today.com on 29MAR2013).

2. UAV Platforms

Unmanned Aerial Vehicles can prove to be a valuable asset in implementing QR codes for visual communications. If extended range is required in order to transmit and receive a message without being detected, a UAV might be launched from a surface ship with pre-programmed coordinates, fly to the ship sending the message, capture the QR code with a photograph, and then return to its home vessel. With improved technologies, the UAV can even possibly decode the message on board and transmit the message back to the receiving ship once in range. Unmanned Aerial Vehicles are a viable option for transmitting and receiving messages between units operating beyond line-of-sight.

Figure 25. ScanEagle UAV in flight (From www.naval-technology.com on 29MAR2013).

E. TACTICAL APPLICATIONS OF QR CODES FOR FLEET COMMUNICATIONS

1. Underway Replenishment

QR codes might become useful for underway replenishment between two vessels at sea. Underway replenishment is the transfer of fuel and stores from a supply ship to another ship and are what enables ships to stay at sea for extended periods of time. Voice communications and flag hoist communications are traditionally used when conducting underway replenishment. The evolution has the ability to become much more automated if QR codes for communications are implemented. QR codes can provide an RF free evolution in the event of emissions control being in place. A code might be displayed on board the refueling vessel stating "We are ready for you to come alongside." The receiving ship then responds with its own message of "I am making my approach." The entire evolution may possibly be done by displaying QR codes rather than communicating via voice methods. This may perhaps lead to a smoother evolution with less opportunity for error. Once the ships are alongside, instead of firing a shot line over with the Phone and Distance line, codes can be continuously displayed on the bridge wings in order to determine lateral separation between the ships based on the size of the QR code being displayed.

Figure 26. Two ships conducting underway replenishment at sea (From www.seaforces.org on 27MAR2013).

Usually, ships use the Phone and Distance line to establish voice communications and provide a method of determining lateral separation. The use of QR codes during underway replenishment can result in the elimination of watch stations on the forecastle and allow the Commanding Officer (CO) and Officer of the Deck (OOD) a simple method of determine safe distance and speed in order to more effectively maintain proper station. The only downside of using QR codes during underway replenishment is due to the sea state. If the ships are rocking too much, it may be difficult to get an accurate picture of the QR code, which might affect its readability and decoding. This is generally, not an issue due to the fact that most UNREPs are done in low sea state, but is something worth thinking about. If visibility is affected to the extent that QR codes are not a viable communication option, infrared technology may be employed to alleviate this issue. Figure 27 provides an illustration of the various flag signals used during underway replenishment between two or more vessels at sea.

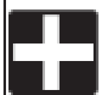
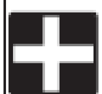
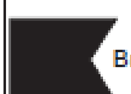
SIGNAL	MEANING
 Romeo Displayed on fore yardarm on side rigged	CONTROL SHIP At the dip: Am steady on course and speed and am preparing to receive you on side indicated. Close up: Am ready for your approach. Hauled down: When messenger is in hand.
 Romeo Displayed on fore yardarm on side rigged	APPROACH SHIP At the dip: Am steady to come alongside. Close up: Am commencing approach. Hauled down: When messenger is in hand.
 Prep Displayed at the outboard yardarm	RECEIVING SHIP At the dip: Expect to disengage in 15 minutes. Close up: Replenishing completed; am disengaging at final station. Hauled down: All lines clear.
 Bravo	BOTH SHIPS Where best seen: Fuel or explosives are being transferred. DELIVERY SHIP At the dip: Have temporarily stopped supplying. Close up: Fuel or explosives are being transferred. Hauled down: Delivery is completed. RECEIVING SHIP At the dip: Have temporarily stopped receiving. Close up: Fuel or explosives are being transferred. Hauled down: Delivery is completed.

Figure 27. Flag hoist meanings for underway replenishment evolution communications (From Naval Warfare Publication Underway Replenishment NWP 4–01.4).

2. Landing/Launching Helicopters

Launching and recovering helicopters are evolutions that require much coordination and communication in order to execute successfully. The helicopter maintains constant voice communications with the ship it is assigned to while taking off and landing, which means that RF energy is being emitted. Launching and recovering a helicopter in an emission controlled or restricted environment can be difficult due to the reliance on voice communications that the Fleet has become accustomed to. A simple front mounted camera might allow the helicopter to read and decode important messages when landing or launching. Messages can be transmitted back and forth between helicopter and ship, without emitting any energy into the electromagnetic spectrum, which allows the two assets to remain radio silent for the duration of the mission or exercise, something that is extremely important in hostile territory or an A2AD environment.

3. Formation Steaming

When ships are operating or are deployed with a Carrier Strike Group or Expeditionary Strike Group, precision formation steaming is important and requires close coordination and flawless execution. Due to the close proximity to other vessels, there is little room for error, because the slightest miscalculation or misunderstanding might result in disaster. If each ship in the battle group is equipped with the proper equipment, camera, and QR code display technology, executing turns, course or speed changes might be accomplished easily when the group commander displays a maneuvering code and has the rest of the ships decode, display proper responses, and then execute the maneuver.

This method is much quicker and less confusing for the watch standers on each bridge watch team. Today, most tactical signals for maneuvering in a group of ships are sent over FLTTAC, which requires the watch stander to first hear the message being transmitted, refer to a book of signals and then decode the message before sending an acknowledgement of receipt. This is time consuming and often times, the code takes too long to get decoded and executed due to the lack of experience and training. A software system that can automatically decode the QR messages faster increases efficiency of the maneuvers. A complete list of tactical signals used for formation steaming can be found in ATP 1 Volume 2, Allied Maritime Tactical Signal and Maneuvering Book.

4. Well Deck Operations

Voice communications in conjunction with flag semaphore are the most common forms of communication when conducting well deck operations with amphibious assault vehicles from an amphibious vessel. Landing Dock Ships conduct launches and recoveries of amphibious assault vehicles such as LCACs, AAV’s, LARC and LCU. Orders and instructions are conveyed from the well deck control officer to the vehicles via flag semaphore signals and voice communication. QR codes may possibly be displayed in the forward end of the well deck and be visible to all amphibious assault crafts launching, landing, and moving to different locations within the well deck.

Figure 28. Well deck view of a surface ship recovering or launching an LCAC (From www.navsource.org on 29MAR2013).

5. Small Boat Operations

Small boats play a crucial role in the Surface fleet as they perform many different important tasks such as port security, oil platform defense and are a necessity for executing VBSS operations and boarding other ships. Transmitting and receiving information is usually accomplished by bridge-to-bridge radio, but with the proper technology, might be done by communicating with QR codes. The larger ship can display the code on the superstructure and the small boat is able to receive the message without violating emissions control or the electromagnetic spectrum. Mounting the proper display on the small boat might prove to be a difficult task, but with the proper technology, it is a strong possibility. This can allow for the small boats to remain operationally effective while maintain radio silence.

6. Identification Friend or Foe/Neutral (IFFN)

QR codes prove useful as a method of identifying units such as aircraft, ships and ground vehicles. Identification Friend or Foe/Neutral (IFFN) is common practice today and allows tactical units to determine who is friend and who is an adversary. QR codes can be placed on the underside of an aircraft's wing, which allows for other units to take a picture of it, scan it, and get the required information in order to determine its status. In addition, QR codes provide ad-hoc dissemination for vehicles and other units, increasing the effectiveness of IFFN. The ability to rapidly develop and deploy IFFN codes in the field, on the fly can provide greater flexibility than is currently possible. Worldwide availability of QR code printing and scanning capabilities means no more additional capability is required to deploy a QR tactical application. An additional application of QR codes with regard to IFFN is that of screening refugees or pirates on board a naval vessel. QR codes can be utilized in a manner that allows additional information to be gathered in a situation that requires it as well as provide hidden information in the QR codes.

7. Medical Use of QR Codes

Medical use, such as triage might also benefit from QR codes. QR codes can be used as an indicator or a method for nurses to identify what type of treatment each patient requires. The use of QR codes in the medical field can provide an expedited method of diagnosing and determining the degree of care required by each patient and speed up the process of providing care and treatment. The use of QR codes in the medical field are a strong possibility and can provide further benefits and capabilities if implemented correctly.

F. ALTERNATIVES TO QR CODES FOR FLEET COMMUNICATIONS

QR codes for fleet communication offers many advantages and can provide tactical units with a new and effective way to communication visually with one another and avoid detection by adversaries due to the fact that QR code transmission does not emit RF energy into the EM spectrum. There are other possibilities and alternatives to explore in addition to using QR codes. Laser communications are an option to consider if QR codes prove to be ineffective. Currently, there is no policy prohibiting the use of laser technology at sea, which means that this area of technology can be implemented in the future if the technology is developed. Laser communications can provide an advantage to the fleet such as an extremely high throughput of data, but do not come without drawbacks. Pointing a laser at another ship in order to transmit a message might present a few issues for the receiving ship. The receiving ship might make the incorrect assumption that the transmitting ship is an adversary and is really targeting them with a laser, which can lead to other issues and potentially escalate the situation. Although lasers pose a few issues without much exploration, it is necessary to explore laser communications as an alternative to QR codes.

In addition to laser communications, digital flashing light is another possible method to defeat HERO and EMCON using a visual communications method. Traditional flashing light communication does not emit any RF energy and is a relatively covert method of communicating. It has been an effective method of visual communication throughout history and can possibly be made into a more automated, quicker, and more efficient method if a few technologies are developed and implemented.

G. CHAPTER SUMMARY

There are many different platforms that can benefit from a communications system that uses QR codes. All military units are susceptible to emissions control and are still expected to maintain effective command and control, as well as communications with other units/vessels. It is not be difficult to mount the proper displays on ships, aircraft, small boats, helicopters and amphibious assault vehicles. If each unit was outfitted with the proper display, camera equipment, and software, QR codes for communications can be an extremely effective system.

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VIII. RESEARCH METHODS

A. CHAPTER OVERVIEW

Baseline distance and angle simulation used during the research of QR codes are described and documented in this chapter. An accurate baseline will allow prediction of the performance of any given image capturing technology. In addition, field experimentation to include distance validation, satellite experimentation, and UAV experimentation are described.

B. SIMULATION

Simulation was conducted by varying QR code size to simulate various distances in order to predict maximum distances at which various optical devices could resolve a QR code for decoding. The outcome of this simulation are the charts in section X.E.1 (figure 65, 66, and 67), which correlates the image device configuration to the size of the image captures, resulting in the ability to predict the performance of any sensor/lens combination. The chart, based on the size of the image predicts with relative certainty the maximum distance at which a device can resolve a QR code based on the pixel density of its sensor, the focal length of the lens and the physical size of the QR code.

Critical characteristics that factor into this simulation are broken into two categories, digital array performance and camera performance characteristics. The most common array performance measures are read noise, charge well capacity, and responsivity. Minimum signal, maximum signal, SNR and dynamic range can be derived from these measures (Holst, 1998).

1. Baseline Distance Simulation

This test simulated the reading of QR codes from various distances by using a proven distance at which the test QR code image could be decoded while varying the size of the displayed image. For each device tested, the maximum simulated distance for QR code resolving was determined and plotted against the pixel densities listed below. A controlled indoor environment was used in which light levels and capture distances were held constant.

Model	**Resolution** (Megapixels)	**Sensor Size** (mm x mm)	**Sensor Well Density** (Megapixels per mm^2)
iPhone 4S	8	4.54 x 3.42	0.51
Canon Powershot SD880	10	6.2 x 4.6	0.35
Canon 5D MkII	21.1	36 x 24	0.024
JVC GY-HD200 720p	0.9	6 x 4.8	0.032
JVC GY-HM750 1080p	2.1	6 x 4.8	0.072
Canon DC420	1.07	2.4 x 1.8	0.247
GoPro HERO3	8.3	6.17 x 4.55	0.295
WorldView-1 Imager	24.9	Unknown	Unknown
WorldView-2 Imager	33.6	Unknown	Unknown

Figure 29. Imaging equipment characteristics for simulation and field experimentation.

Four categories of simulation occurred: Still image capture of digital image display, still image capture of printed image display, video capture of digital image display, and video capture of printed image display. For digital image display, the test image was initialized at 17 inches wide by 17 inches tall (100%) and varied in 1% decrements to a minimum size of 0.85 inches by 0.85 inches (5%). For printed image display, the test image was printed in 1% increments starting from 0.32 inches by 0.32 inches (5%) to 8 inches by 8 inches (100%).

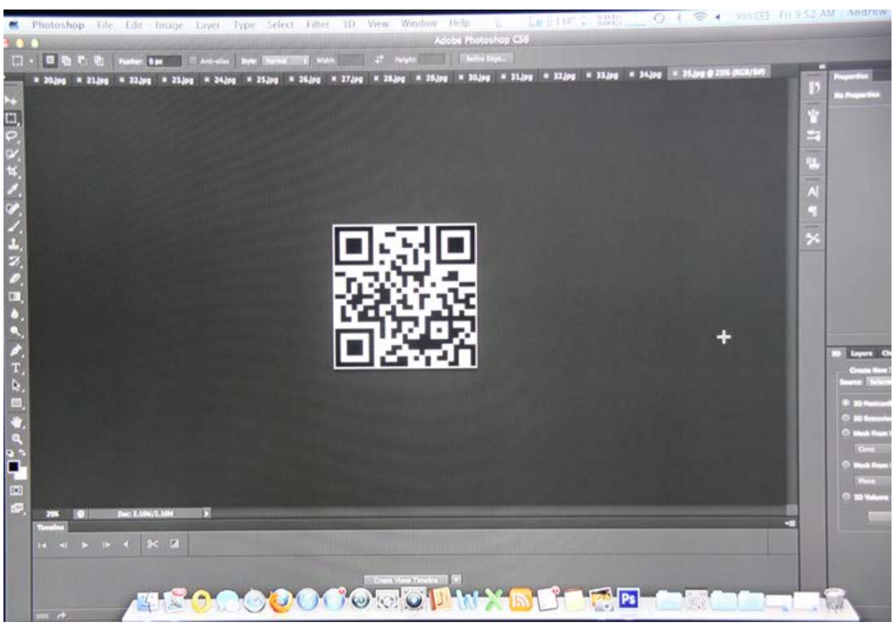

Figure 30. Capturing a digitally displayed 35% QR code image during simulation.

Figure 31. Capturing a print displayed 80% QR code image during simulation.

2. Angle Simulation

This test simulated the reading of QR codes from various angles by using a proven distance at which the test QR code image could be decoded while simulating various angles of the displayed image. For each device tested, the maximum simulated angle (measured against the perpendicular) for QR code resolving was determined. A controlled indoor environment was used in which light levels and capture distances were held constant.

Four categories of simulation occurred: Still image capture of digital image display, still image capture of printed image display, video capture of digital image display, and video capture of printed image display. For digital image display, the test image was initialized at 13.25 inches wide by 13.25 inches tall and varied in 1 degree increments off-perpendicular to a maximum angle of 85 degrees. For printed image display, a 4 inch tall by 4 inch wide test image was varied from 0 degrees off-perpendicular to 85 degrees.

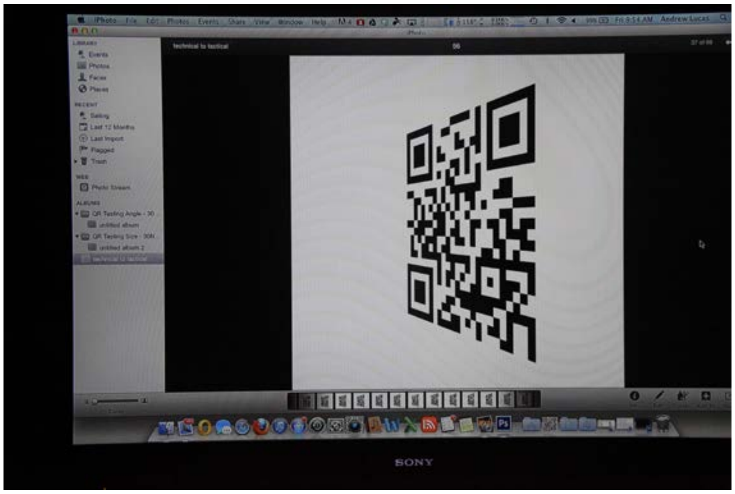

Figure 32. Capturing a digitally displayed 56 degree off-perpendicular QR code image during simulation.

Figure 33. Capturing a print displayed 80 degree off-perpendicular QR code image during simulation.

Figure 34 shows an extensible 3D (X3D) tool useful for displaying a QR code at various angles. This tool allows a user to easily simulate angles as much as 90 degrees off-perpendicular and makes further angle simulation testing simple. Compared to the manual methods used in angular simulation discussed, the X3D simulator greatly reduces image preparation time and discretely displays and specific angle.

Figure 34. X3D image simulation tool displaying "http:qr.nps.edu" at an angle of 36 degrees from a perpendicular viewpoint.

3. Image Preparation

For all simulations, a QR code generated from the RACO Industries' QR Code Barcode Generator was used (http://www.racoindustries.com/barcodegenerator/2d/qr-code.aspx, 20NOV2012). This generated code has the following parameters:

Version	2
Error Correcting Code	L (7%)

Size	25 X 25
Max Alphanumeric Capacity	47 characters
Value	From technical to tactical

Table 4. Test QR code image parameters.

Figure 35. Test QR code image: "From technical to tactical." Version 2, ECC L (7%), 25 x 25 QR bits. Note the necessary standards-compliant inclusion of the quiet zone 4 QR bits wide.

For digital display, the QR code was resized so that it was as large as possible yet still fit on the screen of the test display. This initial QR code was considered 100% for digital display purposes. Using Adobe Photoshop, the 100% image was decreased in size in 1% increments down to the smallest size of 5%. Each sized increment was saved as its own image test file. For the angular simulation, an initial QR code was saved and labeled as zero degrees representing a straight-on view of the code or a view from the perpendicular of the plane it occupies. Again, using Adobe Photoshop, the image was rotated about the Z-axis in one degree increments to a maximum simulated angle of 85 degrees. Each angled increment was saved as its own image test file.

For the printed displays, the QR code was resized so that it was as large as possible yet still fit on a single sheet of 8.5" x 11" paper. This initial QR code was considered 100% for printed display purposes. Using Adobe Photoshop, the 100% image was decreased in size in 1% increments down to the smallest size of 5%. Each sized increment was printed. For the angular simulation, the angular QR codes used for digital display were each printed on individual sheets of 8.5” x 11” paper.

C. FIELD EXPERIMENTATION

Field experimentation was conducted from October 2012 through April 2013 to analyze the benefits of the various technologies in an end-to-end assessment of the QR code communication chain. Specifically, equipment was assessed based on image sensor resolution and optical focal length. This will help identify the ideal technologies to enable QR code communications with acceptable tactical performance parameters.

Range testing was used to validate the distance simulation by recreating the simulated events using actual distances. A large version of the test QR code measuring 37.5 inch x 37.5 inch was constructed on a plywood stand for longer range testing. The plywood was painted white to provide the QR code background and 1.5 inch x 1.5 inch QR bits were glued to represent the test pattern.

Figure 36. Field testing QR display stand constructed of basic lumber and plywood. Test QR code image: "From technical to tactical." Version 2, ECC L(7%), 25 x 25 QR bits, 37.5 inches x 37.5 inches.

1. Range Determination

Initial range determination testing took place in the Spruance courtyard next to Spanagel Hall at NPS. At this location, a maximum possible LOS for testing of approximately 220 yards was achievable. Images of the test QR code were collected using the iPhone 4S, Canon SD880, Canon 5D, Canon DC420, JVC GY-HD200 and JVC GY-HM750. With each camera, images were captured at approximately 10 yard intervals from 20 to 200 yards.

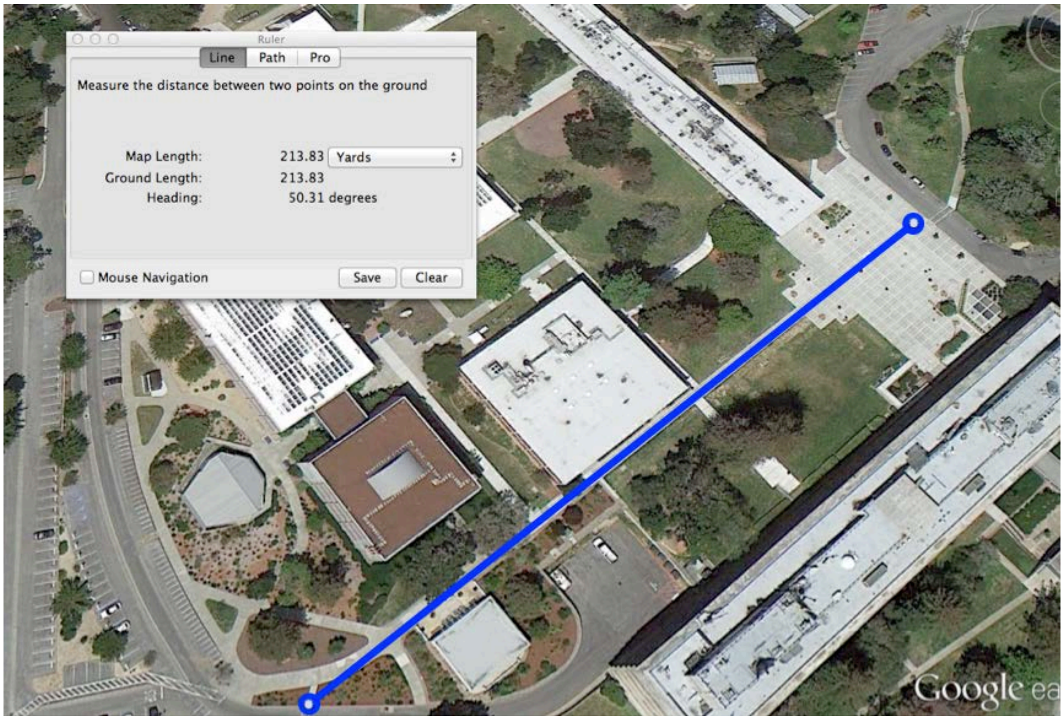

Figure 37. NPS LOS Location: 215 yards available between the Hermann Hall circle and the main gate (After http://maps.google.com).

Distances of from the point of each captured image to the test QR code were measured using a Bushnell Laser Range finder. In Figure 38, the planter on the right was 16 yards and the picnic table on the left was 38 yards from the QR code.

Figure 38. Test Image Placement at NPS in the Spruance courtyard next to Spanagel Hall facing the Hermann Hall Circle.

Range determination testing beyond 200 yards took place at the Fort Ord Motor Pool lot. At this location, a maximum possible LOS for testing of approximately 650 yards was achievable. Images of the test QR code were collected using the iPhone 4S, Canon SD880, Canon 5D, Canon DC420, JVC GY-HD200, JVC GY-HM750, and GoPro HERO3. With each camera, images were captured at approximately 10 yard intervals from 200 to 500 yards.

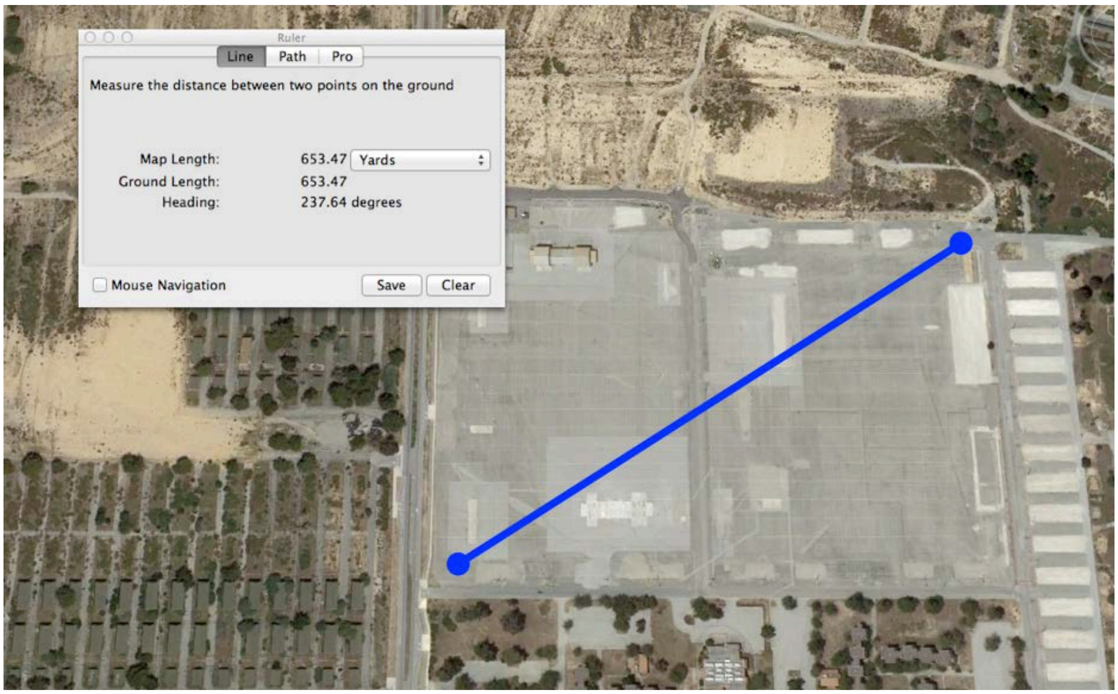

Figure 39. Fort Ord LOS Location: 650 yards available diagonally across the asphalt lot at the motor pool (After http://maps.google.com). .

Figure 40. Test image placement at the Northwest corner of the motor pool lot at Fort Ord.

As with the range testing at NPS, the distances from camera to test image were measures using a Bushnell Laser Range Finder.

Figure 41. Bushnell Elite 1600 ARC laser range finder used for distance determination during all field testing. Capable of determining distances of 6 to 1600 yards (From www.bushnell.com on 23MAR2013).

2. Satellite Capability Demonstration

To demonstrate the ability to send data to high altitudes either to aircraft or spacecraft, a large QR code was painted on the roof of King Hall. A field of white exterior latex paint was applied with a sprayer to the rooftop in a square pattern approximately 45 feet by 45 feet. Within the background, black 1.64 foot QR bits were masked and sprayed to match the test QR code pattern. 1.64 foot QR bits were selected based on the anticipated resolution of the overhead sensors available to capture images.

Figure 42. Complete view of King Hall QR code from atop Spanagel Hall.

Figure 43. Conceptual aerial View of King Hall QR Code using commercial open source overhead imagery (After http://maps.google.com).

Figure 44. Aerial view of King Hall QR code using commercial overhead imagery captured from DigitalGlobe Worldview-1 dated 14 April, 2013.

Official safety procedures were observed while working aloft on King Hall, with corresponding setup/teardown labor costing approximately $1000. Costs included labor to provide roof access, setup of visual safety barriers, and worker safety training. The NPS Public Works department provided an industrial paint sprayer and operational training.

Figure 45. Safety setup at the work area entry point atop King Hall.

Figure 46. Safety setup atop King Hall showing the complete work area including visual safety barriers and entry point.

3. Limited Camp Roberts UAV Testing

A site survey was conducted at Camp Roberts to determine the feasibility of various field tests at that location. During the site survey, the intent was to affix a 16 inch by 16 inch QR code to the underside of the UAV from the ARSENL lab and capture images of opportunity based solely on the set flight plan. ARSENL did not fly, so the opportunity was lost. PSI Corporation was present the same day and was flying their multi-rotor UAV presenting another opportunity for imagery collection. A 16 inch by 16 inch QR code was affixed to the runway and the InstantEye UAV completed several passes over top collecting video. The UAV provided video from three cameras: stock, GoPro, and LWIR. The stock video camera provided standard definition interlaced video. The GoPro camera provided high definition interlaced video. The LWIR camera provided high definition progressive video.

Figure 47. PSI Corp. InstantEye quad rotor UAV.

Figure 48. InstantEye HD video capture of the test QR image on the runway at McMillan Field, Camp Roberts.

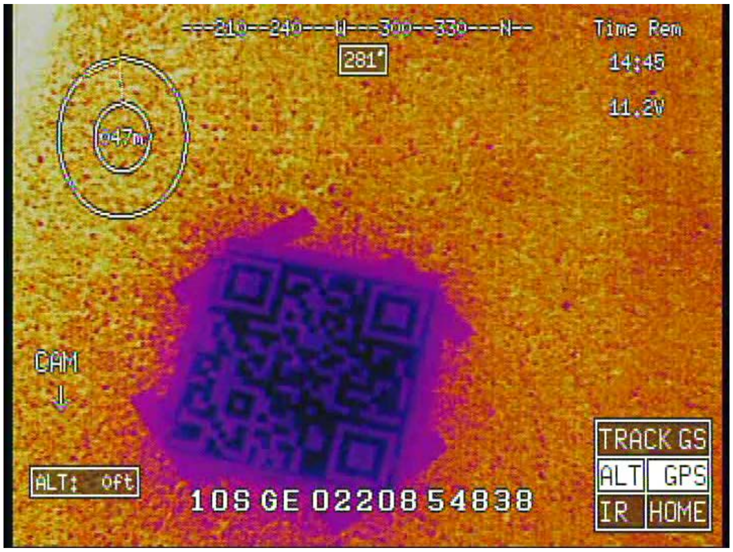

Figure 49. InstantEye LWIR video capture of the test QR image on the runway at McMillan Field, Camp Roberts.

Much more testing is needed. Important future work includes placing a permanent marker on the McMillan airfield runway to support test and calibration during UAV operations conducted as part of ongoing NPS field experiments.

Figure 50. Artist's depiction of potential QR code locations at McMillan airfield using commercial open source overhead imagery (After http://maps.google.com).

D. CHAPTER SUMMARY

Nine different video and still image cameras were used during the simulation and field experimentation portions of this research including commercial satellite imagers. Results for each type of camera were documented following the baseline simulations, field experiment validations, and satellite and UAV demonstrations.

IX. EXPERIMENTAL RESULTS AND ANALYSIS

A. CHAPTER OVERVIEW

1. Maximum Range Capabilities

Table 4 shows the maximum distance for each camera that the QR code test image was successfully captured and decoded. In all cases, with the exception of the iPhone 4S, digital image magnification was required for success. For the iPhone 4S, secondary evaluation provided no range increase over direct evaluation of raw image.

Still Image Cameras		Video Cameras	
iPhone 4S	67	Canon DC420	284
Canon SD880IS	85	JVC HD200	345
Canon 5D MkII	428	JVC HD750	457
		GoPro HERO3	40

Table 5. Maximum distances in yards at which a QR code was successfully captured and decoded for each camera.

2. Equipment Variances

It is important to note that comparisons between differing equipment are general, but each camera and each lens has its own inherent variations based on construction and manufacturing tolerances. These variations are not controlled for in our experimentation.

Because two apparent variables emerged when classifying the image capture equipment, a Camera Capability Factor (CCF) was defined to more appropriately organize the data. The capabilities of each imaging device are mainly dependent on the image sensor resolution and the size of the lens. To combine these into a single variable, the Camera Capability Factor (CCF) was defined as follows:

$$Camera\ Capability\ Factor\ (CCF) = Resolution \times Focal\ Length$$

where the resultant number is measured in MegaPixels X mm.

3. Result Categories

In all cases, image performance results in one of three categories: direct evaluation, secondary evaluation, or unsuccessful evaluation. Direct evaluation is the successful decoding of a QR code using QR Sight, a desktop application, directly from raw image data. Secondary evaluation is the successful decoding of an enhanced QR code using a mobile app (Google Goggles or QRReader) following unsuccessful primary evaluation. Enhancement was simply in the form of displaying the captured image on a computer monitor and increasing it in size. No complex processing occurred in this method. Unsuccessful evaluation was declared if neither of the above two methods resulted in a decoded QR code.

4. Analysis Tools

Multiple tools were used for the analysis of captured data in both still image and video formats. MPEG Streamclip (http://www.squared5.com) and VLC Player (www.videolan.org) were used to extract single frames for analysis from videos. MPEG Streamclip produced JPEG and VLC Player produced PNG images, both in the original resolution of the raw video.

Gnu Image Manipulation Program (GIMP; www.gimp.org) and Adobe Photoshop (www.adobe.com) were used for post collection image manipulation where necessary. QR Sight (www.appvetica.com), QRReader (www.tapmedia.co.uk), Google Goggles (www.google.com/mobile/goggles), and NeoReader (www.neoreader.com) were all used for QR decoding. QR Sight is an OS X-based drag and drop QR reading program. QRReader, Google Googles, and NeoReader are mobile apps for reading QR codes.

B. ANALYSIS METHODS

Simulation and modeling results will compare traditional RF detection and interception probabilities to QR code transmissions to determine the extent to which QR codes are superior. Field experimentation results will be used to compare various technologies to determine the most efficient end-to-end equipment chain in terms of capability, reliability, effectiveness, and cost.

During experimentation, it must be noted that the recognition and decoding of images is dependent on the medium with which it is being displayed. If the QR code is physically printed, the resolution of the QR code is based on dots per inch (dpi) of the equipment used to print the image. If the QR code is digitally displayed, the resolution of the QR code is based upon the technical specification of that display (i.e. 1080p).

One expected result of the baseline experimentation is a formula to predict successful QR code decoding based on the "crispness" of the display. This will be determined by pixels or dots (dpi) per QR bit.

C. SIMULATION RESULTS

1. Distance Simulation

Distance simulation images were captured as discussed in chapter IX.B.1. The full results are listed in Appendix B. The simulation results show the smallest QR images successfully decoded by each optical device. Each of these values was extrapolated to an equivalent distance based on the size QR code used for field experimentation. Using a reference size of 37 inches by 37 inches and a reference distance of 60 inches, the following ratio relates the simulation results to the extrapolated distance:

$$extrapolated\ distance = \frac{reference\ size}{simulated\ size} \times reference\ distance$$

Based on the simulation data, the maximum extrapolated ranges for each imaging device are as follows:

	Still Image Cameras			Video Cameras		
	Technology Factor	Primary Evaluated Range	Secondary Evaluated range	Technology Factor	Primary Evaluated Range	Secondary Evaluated range
	MP x mm	yards	yards	MP x mm	Yards	Yards
Digital QR Code Displays	34.2	10.5	24.5	5.0	18.4	24.5
	50.0	13.6	24.5	11.6	21.6	26.3
	1055.0	24.5	61.3			
Printed QR Code Displays	34.2	33.4	52.5	5.0	36.8	52.5
	50.0	33.4	61.3	11.6	36.8	61.3
	506.4	26.3	52.5			

Table 6. Range extrapolation from simulation.

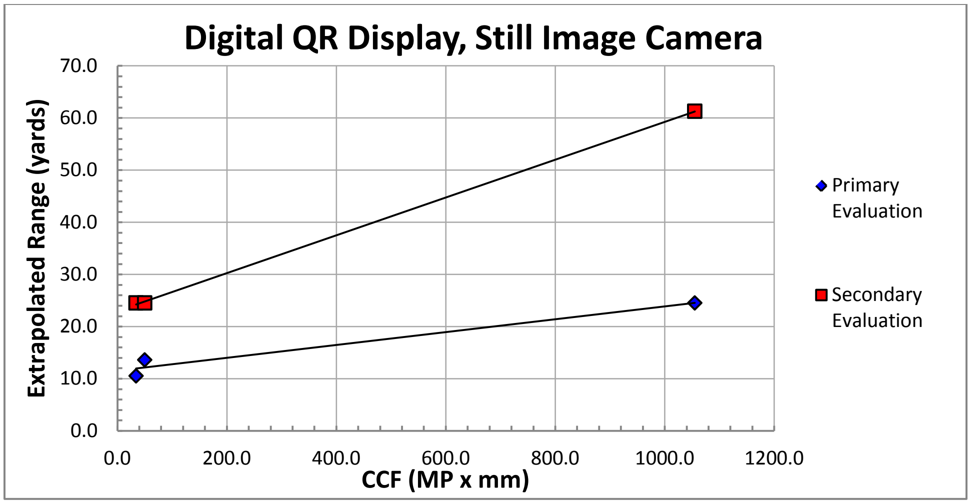

Figure 51. Range extrapolation of simulation data from still image cameras captured from a digitally displayed QR code.

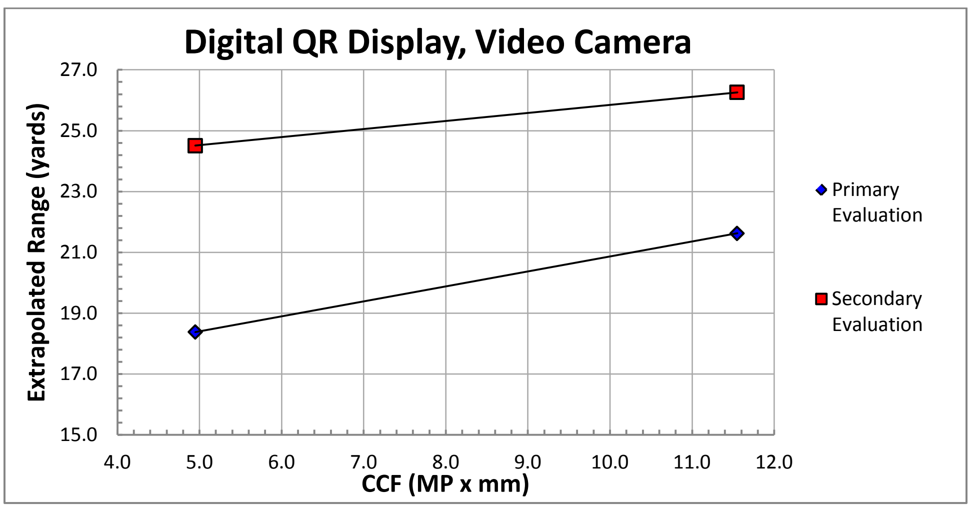

Figure 52. Range extrapolation of simulation data from video cameras captured from a digitally displayed QR code.

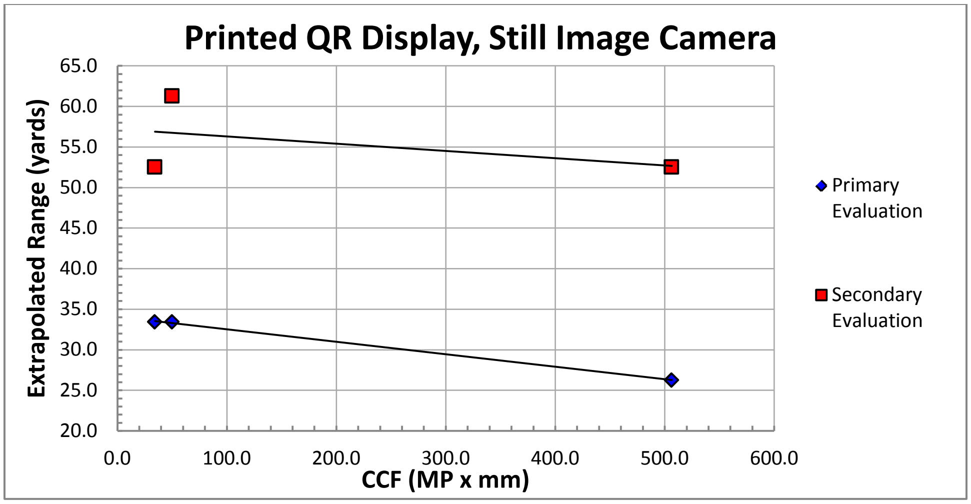

Figure 53. Range extrapolation of simulation data from still image cameras captured from a print displayed QR code.

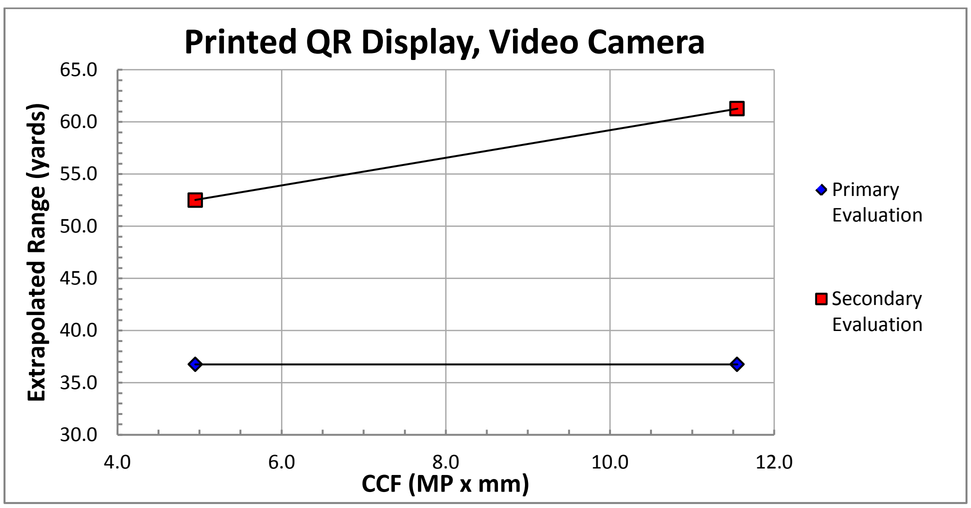

Figure 54. Range extrapolation of simulation data from video cameras captured from a print displayed QR code.

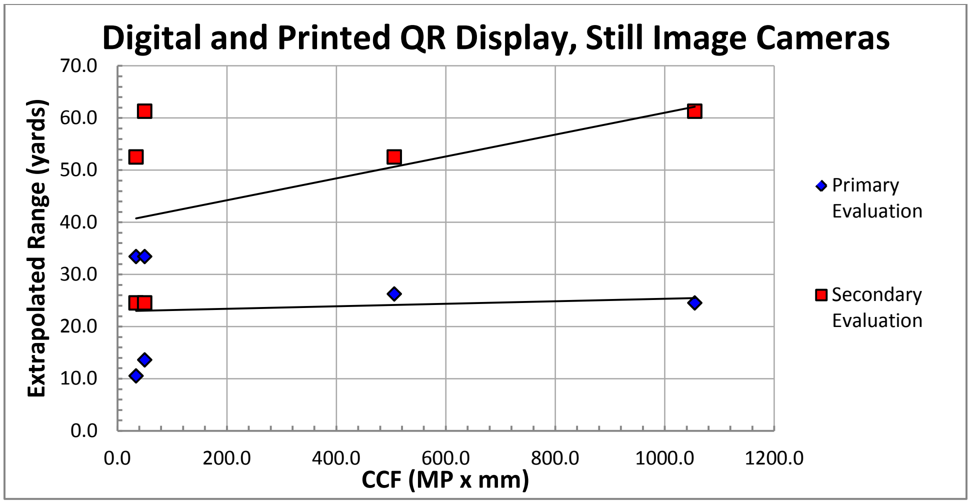

Figure 55. Range extrapolation of simulation data from still image cameras captured from both digital and print displayed QR codes.

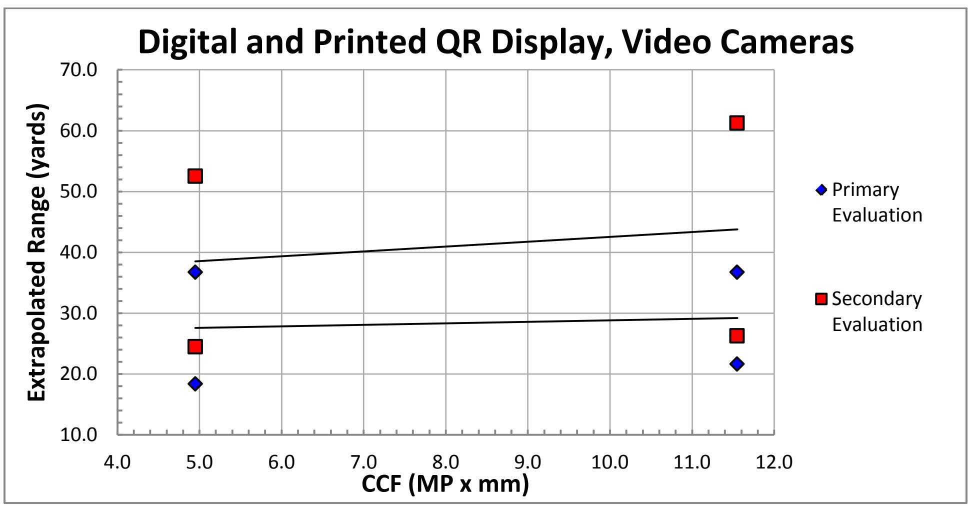

Figure 56. Range extrapolation of simulation data from video cameras captured from both digital and print displayed QR codes.

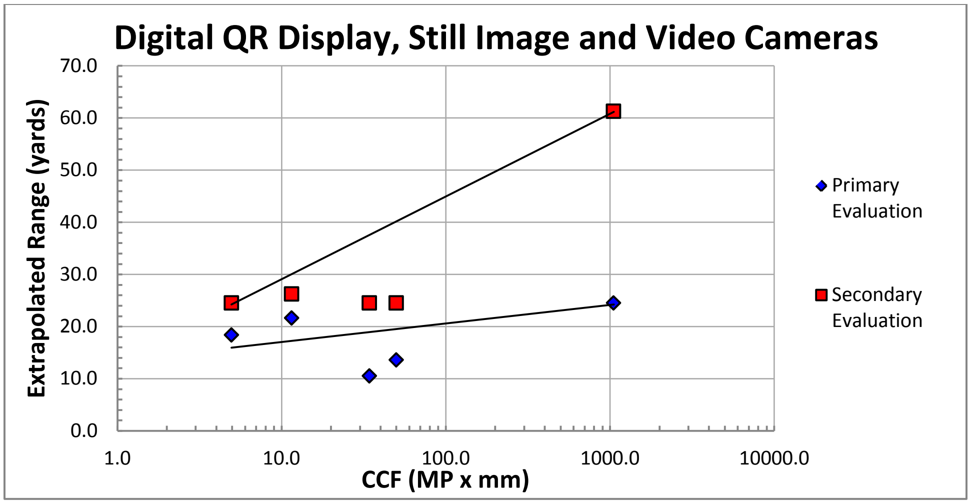

Figure 57. Range extrapolation of simulation data from both still image and video cameras captured from a digitally displayed QR code.

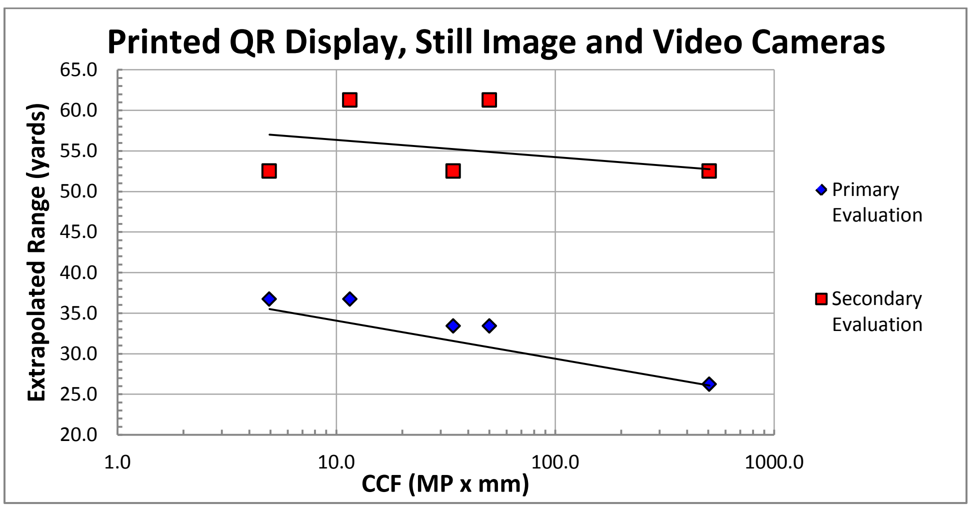

Figure 58. Range extrapolation of simulation data from both still image and video cameras captured from both a print and digitally displayed QR code.

2. Angle Simulation

Angle simulation images were captured as discussed in chapter IX.B.2. The results are as follows:

	Still Image Cameras			Video Cameras		
	Technology Factor	Primary Evaluated Angle	Secondary Evaluated Angle	Technology Factor	Primary Evaluated Angle	Secondary Evaluated Angle
	MP X mm	Degrees	Degrees	MP X mm	Degrees	Degrees
Digital QR Code Displays	34	75	76	5	65	75
	50	60	70	12	68	74
	1055	78	78			
Printed QR Code Displays	34	60	70	5	73	74
	50	55	70	12	42	72
	506	64	70			

Table 7. Maximum off-perpendicular angles of successfully read QR images.

Due to time constraints, full follow-on experimentation of angle analysis was not possible. Because of the implications of field of view (FOV) restrictions on QR code detection, it is important that future work on this research include full angle analysis.

D. FIELD EXPERIMENT (FX) RESULTS

1. Range Determination

Range determination images were captured as discussed in chapter IX.C.1. The full field experiment results are listed in Appendix B. Based on the field experiment data, the maximum ranges for each imaging device are as follows:

Still Image Cameras			Video Cameras		
Technology Factor	Primary Evaluated range	Secondary Evaluated Range	Technology Factor	Primary Evaluated range	Secondary Evaluated Range
MP x mm	yards	yards	MP x mm	yards	Yards
34.24	33	67	11.55		42
200	85	85	49.2	22	26
506.4	81	105	52.91	241	284
1793.5	127	207	79.2	130	345
4220	199	428	99.6	34	40
			184.8	442	457

Table 8. Field experiment maximum range results.

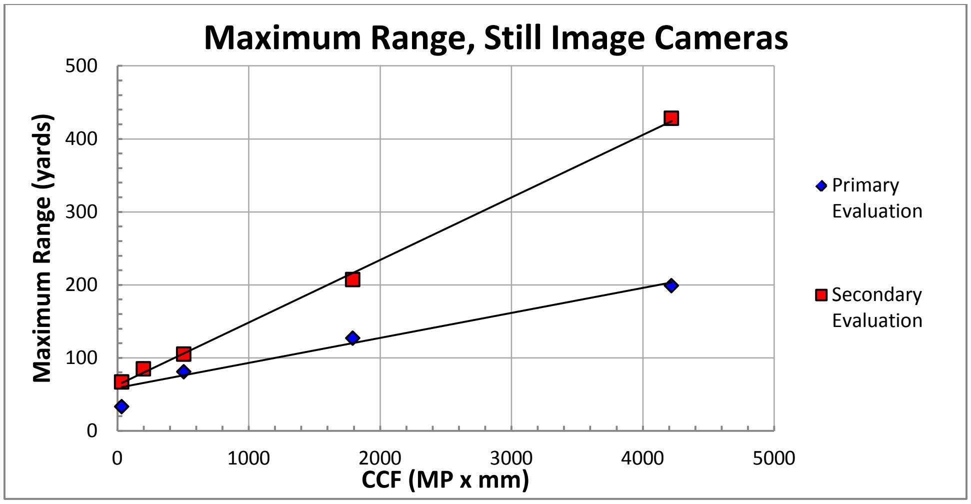

Figure 59. Maximum ranges of successfully read QR codes from images captured from still image cameras.

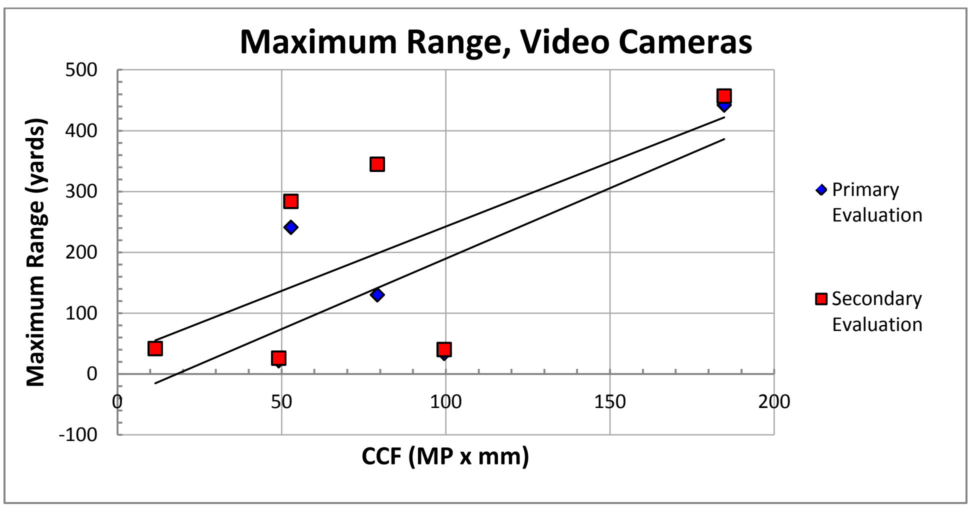

Figure 60. Maximum ranges of successfully read QR codes from images captured from video cameras.

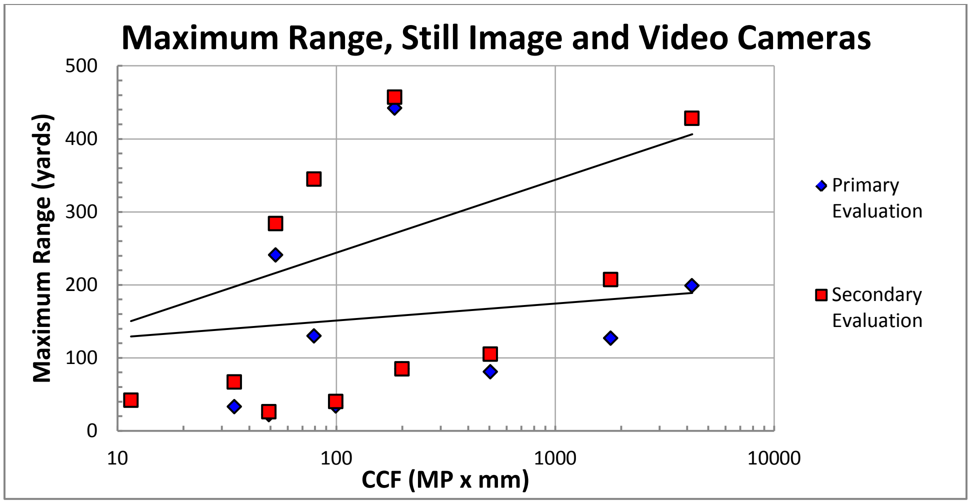

Figure 61. Maximum ranges of successfully read QR codes from images captured from both still image and video cameras.

Extended range testing enabled range evaluation of images captured with a 4K cinematic video camera. This additional field experimentation provided an opportunity to develop an initial image enhancement process as illustrated in Figure 62.

Figure 62. Process steps showing the iterative improvements of a raw captured image resulting in a readable QR code.

In general, if a human can reconstruct a precise QR code from a distorted image. Then image-processing software can do as well or better. The unprocessed image is that of a 100 inch x 100 inch QR code displayed at a distance of 750 yards. The transform step simply rotates the QR code to place the finder patterns on the top right, top left and bottom left corners of the image. The white balance stem applies color correction and adjustment to darken the black QR bits and lighten the white space. The warp/perspective step adjusts full and partial image space for any orthogonal inconstancies restoring the QR code to its original known square state. Edge detection uses a Photoshop and the increased contrast from the white balance step algorithm to discretely define all transitions from black to white. Finally, the difference map is a validation technique that compares the final image to the source image to verify the enhancement process sufficiently reconstructs the QR code.

2. Aircraft and Satellite Demonstration

To date, no images taken by aircraft of the King Hall rooftop QR code have been received. This remains an important area of future work.

Satellite images were captured as discussed in chapter IX.C.2. The resolution of both WorldView-1 and 2 was insufficient to capture imagery of the rooftop QR code with enough clarity for processing by a QR reader. In the case of WorldView-1, reflective light from the white portions of the code washed out the majority of the black portions making the QR code unrecognizable in general. In the case of WorldView-2, the QR code is distinguishable and the 3 QR bit by 3 QR bit portions of the finder pattern appear clearly in the image. It is presumable, from this data that if 3 x 3 image pixels were captured as a single QR bit, the QR code is likely to be readable. It is possible that if the orientation of the QR bits were aligned with the flight path and sensor patterns of the optical imagers on the satellites, then the individual QR bits appear more distinctly (without aliasing errors) and post-processing image enhancement is more likely to recover the original QR code.

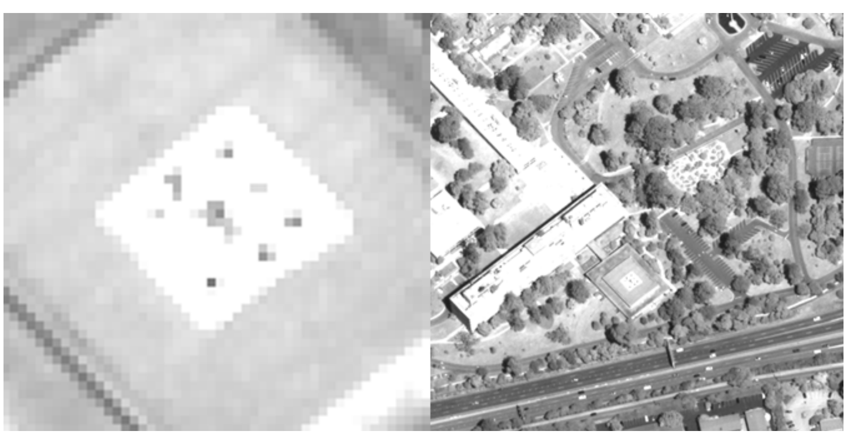

Figure 63. WorldView-1 satellite demonstration imagery (0.5 meter pixel resolution). Not readable.

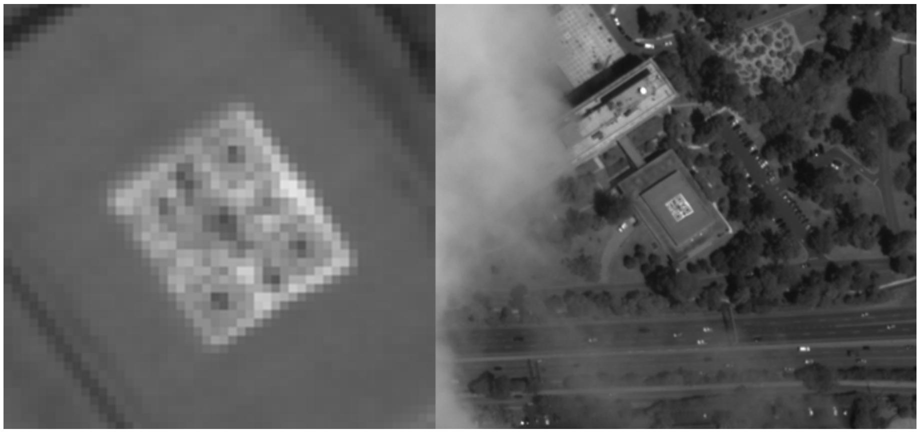

Figure 64. WorldView-2 satellite demonstration imagery (0.46 meter pixel resolution). Not readable.

3. UAV Testing

UAV testing images were captured as discussed in Chapter IX.C.3. Because this experiment was a target of opportunity, it was not controlled similarly to the previous experiments. The video captured demonstrated the ability to locate QR codes from a UAV; however the quality was insufficient to provide any readable images without significant image manipulation.

E. RESULTS ANALYSIS

1. Simulation Analysis

Figures 65, 66, and 67 represent the predictions of QR code performance based on any combination of resolution and optics in an imaging device. In the case of the still image camera, both prediction lines rise as expected, indicating an increase in performance as the product of sensor resolution and lens size increases. In the case of the video camera, both prediction lines decrease as Camera Capability Factor (CCF) increases. This is likely due to an insufficient amount of simulated data collected. When both still image and video camera simulation data are combined, the primary prediction line decreases and the secondary prediction line increases as the CCF increases.

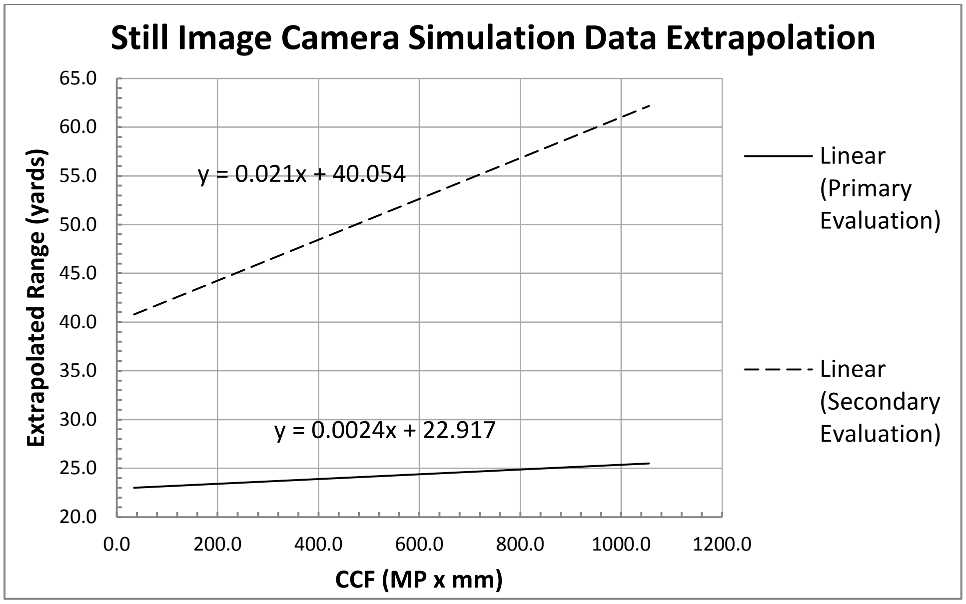

Figure 65. Extrapolation curves from still image camera simulation.

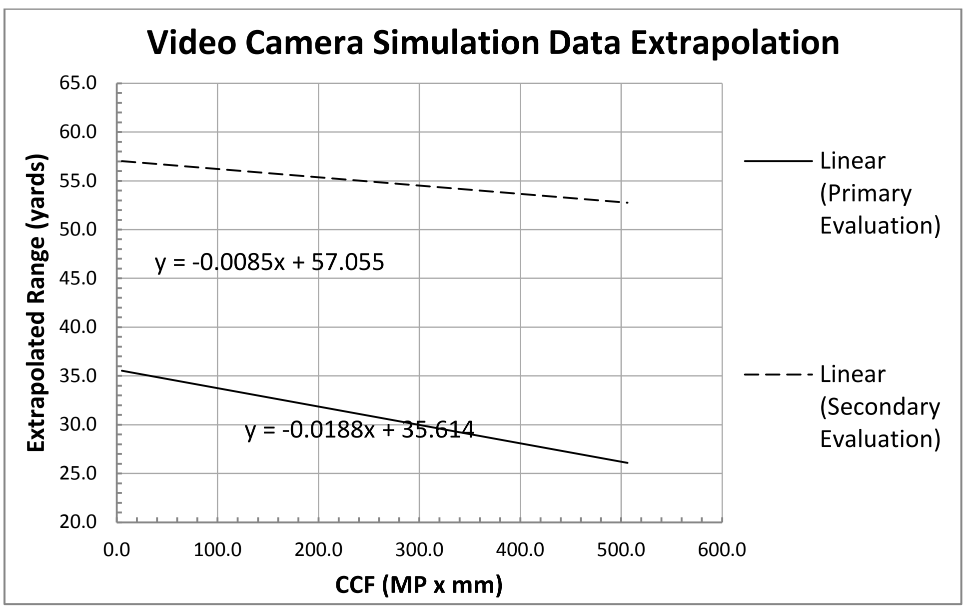

Figure 66. Extrapolation curves from video camera simulation.

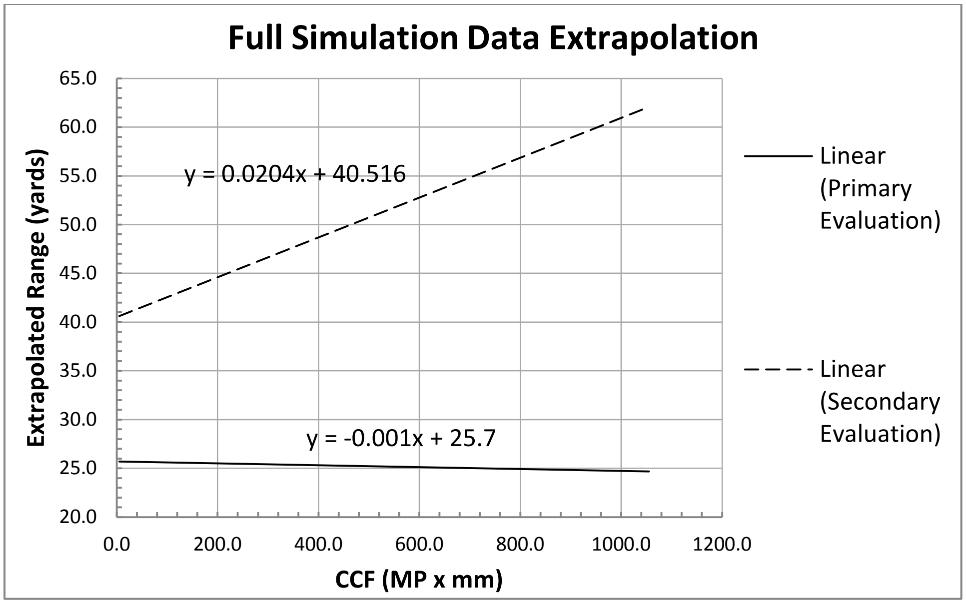

Figure 67. Extrapolation curves from still image and video camera simulations.

In all cases, these prediction curves will benefit from further data collection. In the current state, it is likely that predictions based on these curves will be largely inaccurate. The prediction curves provide the following equations to anticipate the performance of any given lens and sensor combination:

	Primary analysis equation	Secondary analysis equation
Still Image Cameras	y = 0.021x + 40.054	y = 0.0024x + 22.917
Video Cameras	y = -0.0085x + 57.055	y = -0.0188x + 35.614
Still Image and Video Cameras	y = 0.0204x + 40.516	y = -0.001x + 25.7

Table 9. Simulation prediction equations.

2. Field Experiment Validation

The following charts shows extrapolated ranges for all simulation data superimposed on field experiment results. In the case of the still image cameras, the simulation predicted the trends of the field experiment results accurately, but at a differing slope. In the case of the video cameras, the field experiment results were too dispersed to discern a relatable trend. Again, no discernible trends are apparent when both still image and video camera results are combined.

It is important to note, that in all cases, secondary evaluation of QR code images from a given optical device resulted in successful decoding from further distances. Nearly all experimental data met or exceeded preliminary estimates of expected maximum range.

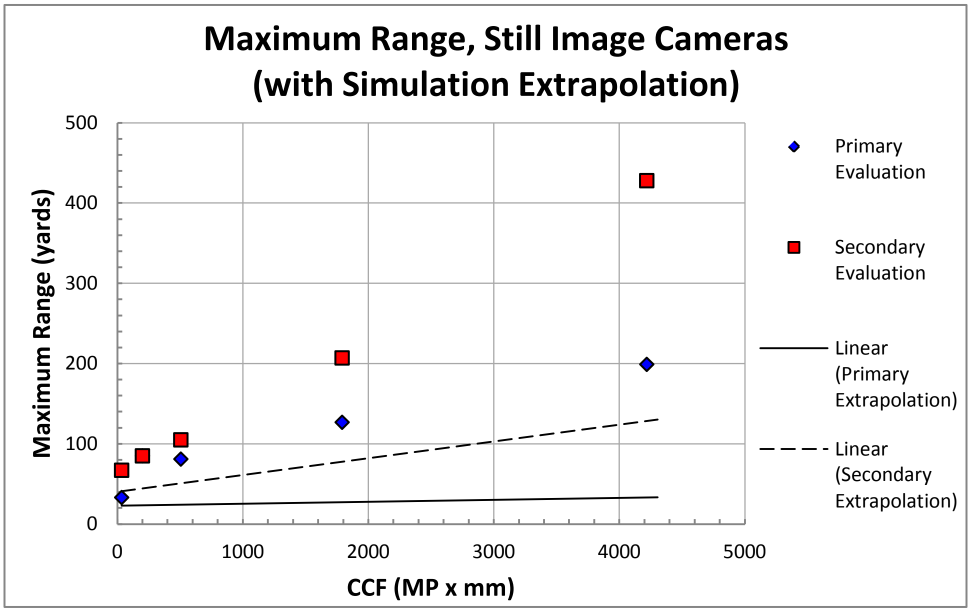

Figure 68. Maximum ranges of successfully read QR codes from images captured from still image cameras superimposed on expected ranges extrapolated from simulation data.

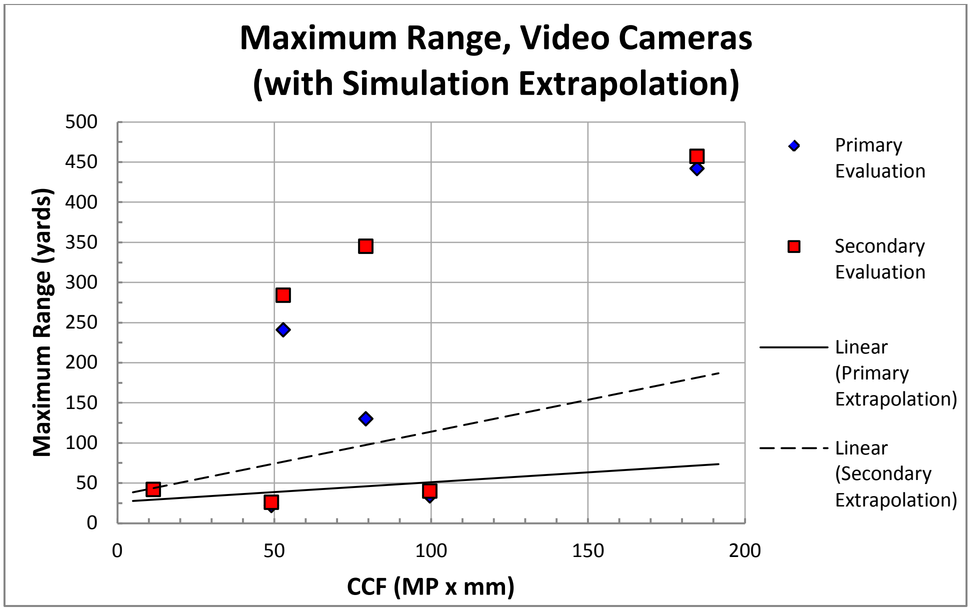

Figure 69. Maximum ranges of successfully read QR codes from images captured from video cameras superimposed on expected ranges extrapolated from simulation data.

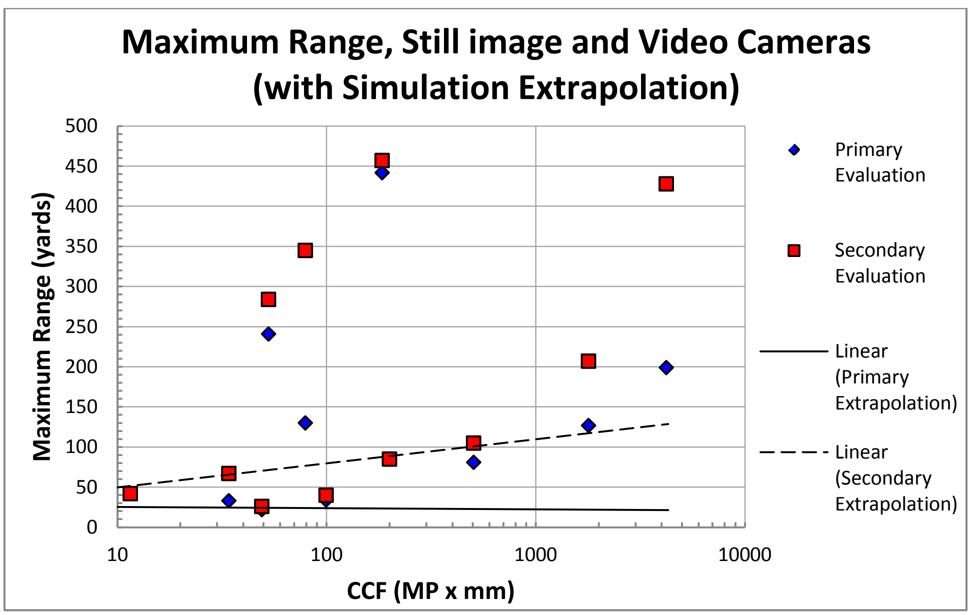

Figure 70. Maximum ranges of successfully read QR codes from images captured from both still image and video cameras superimposed on expected ranges extrapolated from simulation data.

3. Minimum QR Code Sizes

The following charts show the size, in pixels, of the QR bits from images determined to be at the limits of readability. Measurements were taken for both primary evaluation of the raw images by QR Sight and secondary evaluation of the images by mobile QR readers.

Digital Display					
		Primary Evaluation		Secondary Evaluation	
	Camera	Finder Pattern Diagonal (pixels)	QR Bit Size (pixels)	Finder Pattern Diagonal (pixels)	QR Bit Size (pixels)
Still Image Cameras	iPhone 4S	101.9	10.3	44.6	4.5
	Canon SD880	84.9	8.6	45.3	4.6
	Canon 5D MkII	115.3	11.6	38.2	3.9
Video Cameras	JVC HD200	36.1	3.6	26.2	2.6
	JVC HD750	45.3	4.6	35.4	3.6

Table 10. QR bit size, in pixels, from the smallest readable QR code images digitally displayed.

Printed Display					
		Primary Evaluation		Secondary Evaluation	
	Camera	Finder Pattern Diagonal (pixels)	QR Bit Size (pixels)	Finder Pattern Diagonal (pixels)	QR Bit Size (pixels)
Still Image Cameras	iPhone 4S	43.9	4.4	26.9	2.7
	Canon SD880	43.1	4.4	21.2	2.1
	Canon 5D MkII	55.2	5.6	26.9	2.7
Video Cameras	JVC HD200	23.3	2.4	17.0	1.7
	JVC HD750	33.9	3.4	21.2	2.1

Table 11. QR bit size, in pixels, from the smallest readable QR code images print displayed.

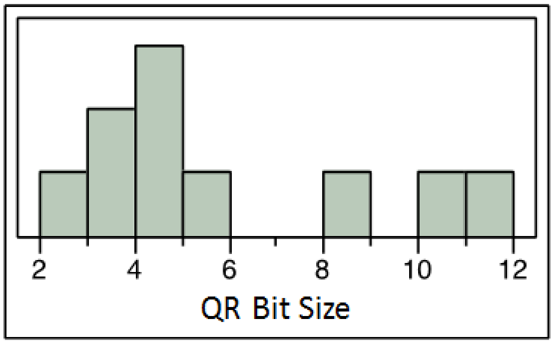

Figure 71. Statistical evaluation of QR bit size data from primary evaluation of simulated data ranges.

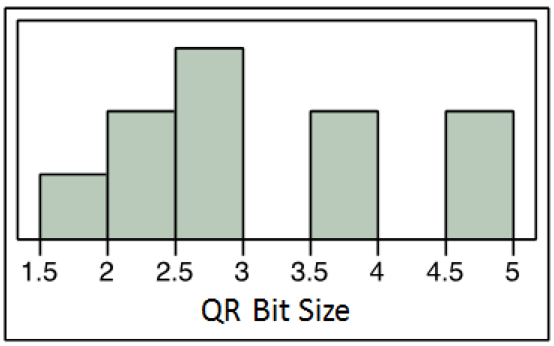

Figure 72. Statistical evaluation of QR bit size data from secondary evaluation of simulated range images.

The mean of the primary evaluation results of the simulation data is 5.89 and the mean of the secondary evaluation results of the simulation data is 3.05. This predicts that these values are the minimum sizes, in pixels, of a QR bit in a QR code that can be decoded using QR sight for primary evaluation and mobile QR reader applications for secondary evaluation. The imaging device sample size is small, therefore it is likely that these numbers are inaccurate until more simulation data points can be collected.

		Primary Evaluation		Secondary Evaluation	
	Camera	Finder Pattern Diagonal (pixels)	QR Bit Size (pixels)	Finder Pattern Diagonal (pixels)	QR Bit Size (pixels)
Still Image Cameras	iPhone 4S	38.2	3.9	19.8	2.0
	Canon SD880	55.2	5.6	none	none
	Canon 5D MkII	65.8	6.6	49.5	5.0
		42.8	4.3	26.6	2.7
		61.6	6.2	28.0	2.8
Video Cameras	Canon DC420	27.6	2.8	25.5	2.6
	JVC HD200	78.5	7.9	24.8	2.5
	JVC HD750	none	none	22.6	2.3
		31.1	3.1	28.3	2.9
	HERO3 2.7K	22.6	2.3	19.1	1.9
	HERO3 4K	21.2	2.1	19.1	1.9

Table 12. QR bit size, in pixels, from highest-range readable QR code images
.

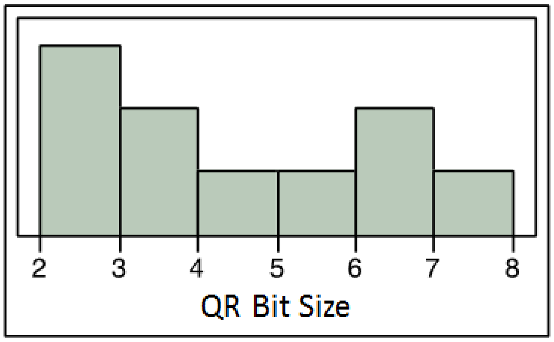

Figure 73. Statistical evaluation of QR bit size data from primary evaluation of experimental range images.

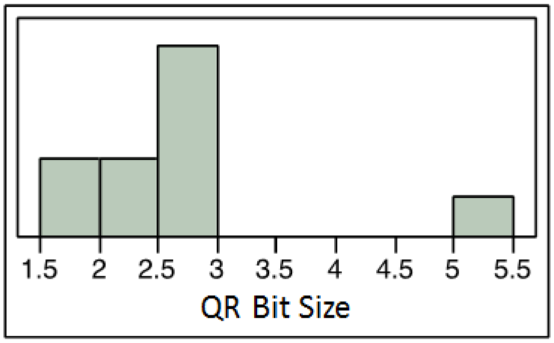

Figure 74. Statistical evaluation of QR bit size data from secondary evaluation of experimental range images.

The mean of the primary evaluation results of the field experiment data is 4.48 and the mean of the secondary evaluation results of the field experiment data is 2.55. The outlier seen in the secondary evaluation of the field results is most likely due to the poor quality of captured images. When compared to the above simulation data, it shows that the simulation estimate provides a more conservative value and that actual results are measurable better than simulated results. Again, the data sample size is small and it is likely that these numbers are inaccurate until more simulation data points can be collected.

One recommendation for QR signaling to satellites is to align the code to be parallel to the expected satellite track direction for maximum overhead resolution when seen from nadir.

Similar to the decoding capability seen with range, in all cases, minimum QR bit size in pixels is smaller when comparing secondary to primary evaluations.

4. QR Code Reconstruction

In Figure 75, an original 4K image is cropped to a single QR bit, revealing that each QR bit occupies a pixel array of 16 x 16. This easily satisfies the minimum requirement of 3 x 3 image pixels. The cropped image is then scaled by 50% in each dimension using a common nearest neighbor (edge preserving) algorithm, and so forth until an approximation of a signal from a standard definition (NTSC VHS) is reached. In the 960 x 480 sample, the pixels that would clamp to black roughly equal the pixels that would clamp to white, so it is indeterminate. Images below that resolution could not be used to reconstruct a QR bit and therefore not useful to reconstruct a QR code.

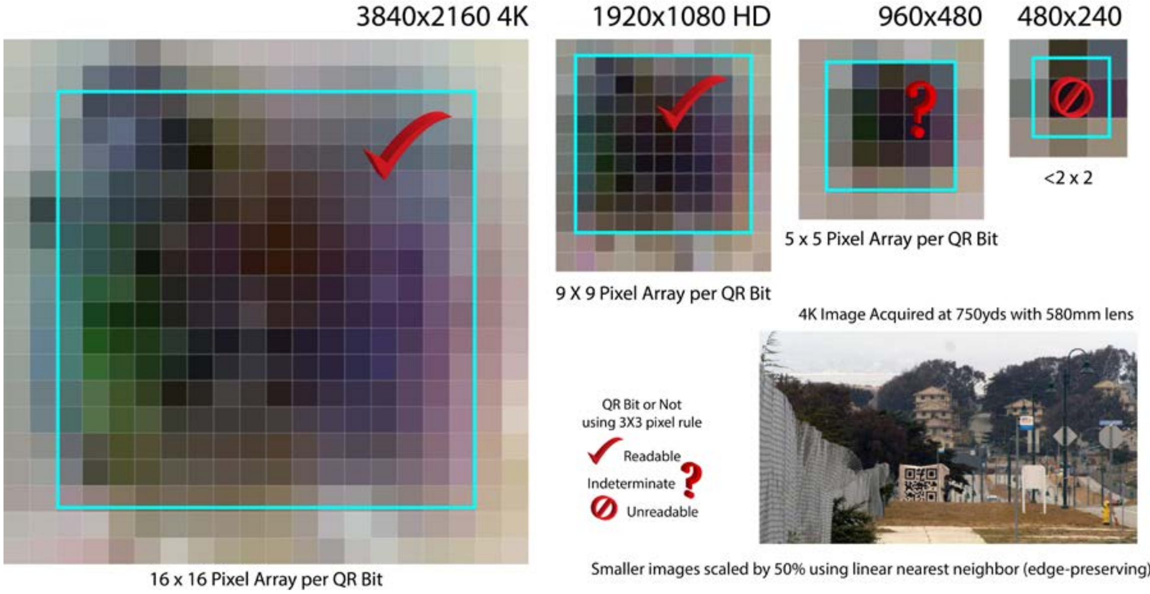

Figure 75. Demonstration of single QR bit reconstruction using 4K video camera image of 100 inch x 100 inch QR code captured at 750 yards.

QR bits read from 2000 yards returned an approximate 5 x 5 image pixel matrix, though because of optical turbulence, the image is noisy. However, it also satisfies the 3 x 3 image pixel rule. Since optical turbulence is much less of a factor over large bodies of water, it is conceivable that transmission would be successful given focal length (580mm) and 4K sensor size at 2000 yards or more (Frehlich, 1992).

It should be noted that since QR codes are generally constructed of black QR bits on a white background, the de-Bayering, or reconstruction of the signal into a color image is likely unnecessary. Pixels are known to be black in Figure 75; yet because of sensor noise or ambient conditions, they are returned as dark brown or grey. Simple image processing such as clamping values below 50% luma as black and above 50% luma as white would compensate for these anomalies. Other, simple image processing steps are illustrated in Figure 62. Advanced, but still common techniques used in computer vision, such as deriving a histogram of gradient vectors could reconstruct a QR code from even very noisy images. This is possible because the QR code itself is constructed so that gradient vectors would be highly predictive of QR bit arrangements.

F. QUALITATIVE RESULTS

Based on the vast amount of images captured, it is clear that a rigorous accountability system must be established in order to usefully organize collected data. The initial cataloging proposal for imagery was to superimpose telemetry data over the image. In a tactical environment, however, there may be no way to control the location of the QR code within the captured image. If the code is positioned in the same location as the telemetry data, there is a good chance that the code would be unreadable. Two cataloging alternatives are available: filename structure and embedded metadata.

With filename structure, in-situ image processing would name the image in the file system with appropriate labels to uniquely identify each image as it is captured and stored in memory. Basic labels will be mandatory such as imager identification, geo-location, date and time. A user can then add additional informational tags such as imager resolution, environmental descriptions, operation name, etc. While this method is thorough, long filenames may become cumbersome.

Metadata simplifies complex labeling by appending each file with encoded data that uniquely describes the image. The labeling structure is identical to the filename method, but the labels themselves are stored within the file itself. The filenames then become arbitrary and the internally recorded label data remains unreadable until extracted by an appropriate software interface.

Field experimentation has shown that there is a significant increase in capability when images are processed and enhanced prior to analysis by a QR pattern decoding program. In most cases ranges nearly doubled when images were simply increased in size, displayed on a computer monitor and evaluated with a mobile QR reader application. Further capability increases occurred when the images are enhanced digitally by sharpening the boundaries and increasing the contrast between the black and white QR bits. This is often necessary when lighting conditions are not ideal as the white QR bits tend to shift in color based on the environment. Custom decoding algorithms could be programmed to incrementally decrease the contrast threshold required for detecting QR codes when a code is not initially detected in an image.

G. CHAPTER SUMMARY

This chapter discussed the results of both simulation and field experiments in order to determine the effectiveness of the various technologies available for detection and decoding of QR codes at longer distances. The most common trend encountered is that of increased capability as the focal length and or resolution of the imaging device increases. Additionally, the introduction of post processing of QR code images drastically increased decoding performance.

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X. CONCLUSIONS AND RECOMMENDATIONS

A. RESEARCH FINDINGS AND CONCLUSIONS

The results of this research show that there are numerous advantages to QR codes for communications in a tactical environment. QR code communication provides numerous advantages over traditional RF LOS communications. Since QR codes can be a visual method of communicating, there are no RF emissions, which greatly reduce the possibility of detection, intercept, and exploitation. RF LOS communications are susceptible to emissions control measures, which reduces the effectiveness of communications. QR codes are a tool that can be used to circumvent emissions control restrictions, much like flashing light, flag semaphore and flag hoist methods. QR codes allow tactical units to communicate efficiently and effectively where radio communications are not permitted and it is necessary to remain undetected.

Although the advantages of QR codes for communications are plentiful, it must be noted that simulation and experimentation uncovered numerous disadvantages as well. Until further technology is tested with QR codes, it is difficult to determine the effects that movement has on a code. All testing was done in a controlled environment, with a stationary QR code. Aboard ships at sea, where this technology can be extremely useful, could uncover problems associated with this. The range at which a QR code can be decoded was roughly five hundred yards with the available technology. This distance is not sufficient enough to be considered a useful communication tool for the fleet. The testing of better technology can most likely reveal that distances of a few miles can be achieved.

Traditional visual communications methods such as flashing light, flag semaphore and flag hoist did not rely on technology in order to transmit and receive messages. The present state of technology associated with QR codes indicates that different environments can have a variety of effects on the transmission and receipt of messages. No testing was done with the presence of fog or reduced visibility, but almost certainly has a negative impact on the transmission of messages via QR codes. Testing did reveal that even a change in lighting or reflection on the code made it more difficult to decode.

B. RECOMMENDATIONS FOR FUTURE WORK

1. QR Code Tactical Decision Aid (TDA)

QR code technology and use for tactical communications has been explored in this thesis, but there are many aspects that remain to be researched and experimented with. If QR code digital communications is to be used in the fleet, it will be necessary to develop some sort of tactical guidance/guidelines for the use of QR codes. In addition to this tactical guidance, a tactical decision aid can prove useful for watch standers and warfighters. Developing a tactical decision aid along with a computer interface might prove useful to tactical units because it allows for the QR code to be captured and decoded all through the computer program. The decoded message might then be displayed at the watch stander's console, drastically reducing the complexity of the visual communication process. Additional description of the Tactical Decision Aid for QR codes can be found in Appendix C of this thesis.

2. Laser Technology Communications

There have been discussions regarding utilizing laser technology for communications due to its higher data rate capabilities; however, there are many disadvantages and risks associated with using lasers for communications in a tactical environment. Research and experimentation can be done to determine what the advantages, disadvantages, and risks are associated with lasers for tactical communications. This type of visual communication method might extend the range of QR code communication, which can prove to be important when operating in an EMCON environment.

3. Aircraft and Airfield use of QR codes

There are many other possible applications of QR codes that are not related to visual communications that can be explored. QR codes can prove effective if displayed on airstrips and runways around the world to convey messages and other vital information to aircraft taking off and landing. Chris Sokol, an employee of the United States Strategic Command is working with Dr. Don Brutzman and is performing research and experimentation on the use of QR codes for aircraft and airfields with an emphasis on airfield and aircraft safety. Additional research and experimentation is needed in this area to determine the value added by QR codes.

4. Probability of Detection Simulation

A probability of detection simulation can compare the probability of detection of a QR code with traditional RF LOS technologies. This will attempt to show that the probability of detection of QR codes is lower than that of current HF, VHF and UHF communications suites. It is believed that a probability of detection simulation will yield results to support the theory that QR codes for communications will be more difficult to detect over RF LOS communications.

5. Obfuscation Methods

Obfuscation methods to prevent unauthorized users from reading QR codes are a vital piece of the puzzle. Should QR codes be implemented in the fleet, it is important to have methods of ensuring that adversaries in the vicinity not be able to decode message transmissions. This topic may be better suited if QR code security in general was explored. Development of additional security measures, other than those mentioned in this thesis, are important as well and can be studied and analyzed.

6. Realistic Environment Testing

Testing of this technology in a realistic environment can be done in order to ensure that this is a viable method of communicating for the fleet. Factors such as sea state, fog, reflections from the sun, sea spray, and rain all have the potential to interfere with and reduce the effectiveness of QR codes. Testing can include ship-to-ship, surface-to-air, and ship-to-shore at a minimum.

7. Tactical Signaling

This implements characters representing longer character strings that commonly occur in messages. For instance, if the first character in a QR code is “U” or “S” it might mean the following message is preceded by “http://” or “https//” respectively. Testing can be done in this area in order to determine if there are methods of shortening a message transmission.

8. Tactical Performance Study

Valuable research can be done in order to determine how the QR code capability will improve tactical performance of various platforms using the technology. How will this capability improve tactical performance for various platforms?

9. Capabilities Beyond Naval Applications

QR codes have the ability to make an impact on other industries as well as the Department of Defense. Researching what capabilities QR codes can provide beyond naval applications might prove important.

10. Flag Semaphore Camera Recognition

Research of camera recognition of image and video capture of semaphore characters and flag movements can provide an extended range of flag semaphore, which can provide the fleet with a valuable visual signaling method.

11. Point-to-Point Protocol

It will be necessary to evaluate the appropriate use of Point-to-Point protocol and possibly develop a new QR code over IP streaming protocol. This can have a major impact on the implementation and use of QR codes in a tactical environment. This future work item is crucial to the future success of QR codes as a visual communication method.

12. QR Codes in the Underwater Domain

Additionally, the tactical applications of QR codes in the underwater domain were not explored due to time constraints. Limiting factors for the use of QR codes in an underwater environment is restricted amounts of light, restricted power, and limited range. Since power consumption of light displays is prohibitive, acoustic modes are likely to be far preferable for this application. QR codes might be employed as a tactic for marking mines or as a docking station for submarines or unmanned underwater vehicles. This capability is limited to short range, and a more viable option may be simpler markers. It might be valuable to explore underwater use of QR code communications.

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APPENDIX A. EXPERIMENT SCHEDULE OF EVENTS

The following experiments were initially planned for this research. Due to time and resource constraints, only experiments B, C, D, and I were completed. The remainder of experiments should be completed as future work.

C. BASELINE DISTANCE SIMULATION

Date: 26 – 30 November 2012

Objective: Determine the most distant readable QR code for each image capturing device through lab simulation.

D. BASELINE DISTANCE VALIDATION EXPERIMENT

Date: 26 – 30 November 2012

Objective: Determine the most distant readable QR code for each image capturing device through field experimentation.

E. BASELINE ANGULAR SIMULATION

Date: 3 – 7 December 2012

Objective: Determine the widest off-perpendicular angle at which a QR code can be read through lab simulation.

F. BASELINE ANGULAR VALIDATION EXPERIMENT

Date: 3 – 7 December 2012

Objective: Determine the widest off-perpendicular angle at which a QR code can be read through field experimentation.

G. PROBABILITY OF DETECTION SIMULATION

Date: 9 – 15 December 2012

Objectives: Determine optimal positioning and initial probabilities for QR code detection through lab simulation.

H. PROBABILITY OF DETECTION VALIDATION EXPERIMENT

Date: 9 – 15 December 2012

Objectives: Determine optimal positioning and initial probabilities for QR code detection through field experimentation.

I. AIRCRAFT/UAV QR CODE DETECTION

Date: 7 – 11 January 2013

Objective: Validate baseline simulation data and demonstrate ability to read a QR code from an aircraft.

J. SATELLITE IMAGERY QR PIXEL AND QR CODE DETECTION

Date: 13 – 19 January 2013

Objective: Validate baseline simulation data and demonstrate ability to read a QR code from an orbiting spacecraft.

K. USV TWO-WAY QR CODE DETECTION

Date: 20 – 26 January 2013

Objective: Validate baseline simulation data and demonstrate ability to read a water vessel mounted QR code in a realistic environment.

APPENDIX B. SIMULATION AND EXPERIMENT DATA

This data represents both simulation and field experiment results. The tables are interpreted with the following legend:

Legend
Decoded by direct evaluation with QR Sight
Decoded only by secondary evaluation despite further range points successfully decoded by direct evaluation
Decoded by secondary evaluation with Google Goggles or QRReader
Not Decoded by any means

Table 13. Simulation and Field Experiment Results Legend

Associated with each imaging device is:

- The focal length of the optics used during the experiment measured in mm.
- The resolution of each image sensor measured in megapixels.
- The Camera Capability Factor (CCF) allowing the results to be related to both the focal length and the resolution of the equipment used for each experiment. The CCF is the product of the focal length and the resolution.

Digital Display					
	Still Camera Images			Video Camera Images	
Sensor	iPhone 4S	Canon SD880	Canon 5D MkII	JVC GY-HD200	JVC GY-HD750
Focal Length (mm)	4.28	5	50	5.5	5.5
Megapixels	8	10	21.1	0.9	2.1
CCF	34.2	50.0	1055.0	5.0	11.6
Image Size (% of 17 in X 17 in)	66	66	66	66	66
	…	…	…	…	…
	35	35	35	35	35
	34	34	34	34	34
	33	33	33	33	33
	…	…	…	…	…
	28	28	28	28	28
	27	27	27	27	27
	26	26	26	26	26
	25	25	25	25	25
	…	…	…	…	…
	21	21	21	21	21
	20	20	20	20	20
	19	19	19	19	19
	18	18	18	18	18
	17	17	17	17	17
	16	16	16	16	16
	15	15	15	15	15
	14	14	14	14	14
	13	13	13	13	13
	…	…	…	…	…
	7	7	7	7	7
	6	6	6	6	6
	5	5	5	5	5

Table 14. Digital Display Simulation Data

Printed Display					
	Still Camera Images			Video Camera Images	
Sensor	iPhone 4S	Canon SD880	Canon 5D MkII	JVC GY-HD200	JVC GY-HD750
Focal Length (mm)	4.28	5	24	5.5	5.5
Megapixels	8	10	21.1	0.9	2.1
CCF	34.24	50	506.4	4.95	11.55
Image Size (% of 13.25 in X 13.25 in)	14	14	14	14	14
	13	13	13	13	13
	12	12	12	12	12
	11	11	11	11	11
	10	10	10	10	10
	9	9	9	9	9
	8	8	8	8	8
	7	7	7	7	7
	6	6	6	6	6
	5	5	5	5	5

Table 15. Printed Display Simulation Data

Range Analysis						
	Still Camera Images					
Sensor	iPhone 4S	Canon SD880IS		Canon 5D MkII		
Focal Length (mm)	4.28	5	20	24	85	200
Megapixels	8	10	10	21.1	21.1	21.1
CCF	34.2	50.0	200.0	506.4	1793.5	4220.0
Range (yds)	19	85	85	3	85	84
	27	93	93	15	93	94
	33	100	100	24	100	105
	41	108	108	34	108	118
	50	114	114	46	114	130
	59	127	127	59	127	143
	67	136	136	71	136	157
	75	143	143	81	143	176
	81	201	201	84	148	189
	89			85	158	199
	95			94	167	207
	100			96	175	222
				105	185	235
					196	249
					201	263
					207	275
						289
						303
						311
						321
						335
						347
						356
						368
						379
						390
						402
						413
						428
						442
						457
						470
						482
						495
						505

Table 16. Still Image Camera Field Experiment Data

Video Camera Range Analysis					
Sensor	Canon DC420	JVC HD200	JVC HD750	GoPro 2.7K	GoPro 4K
Focal Length (mm)	96.2	88	88	12	12
Megapixels	0.55	0.9	2.1	4.1	8.3
CCF	52.9	79.2	184.8	49.2	99.6
Range (yds) Note: Range values are not correlated between columns	43	84	42	6	3
	…	…	…	…	…
	84	130	207	22	7
	97	143	217	26	8
	109	157	227	30	9
	120	…	237	35	14
	134	334	…	40	19
	143	345	257	45	24
	156	355	258		29
	165	367	266		34
	178	377	269		40
	189	387	275		45
	200	397	279		51
	202	408	285		
	213	418	289		
	227	428	294		
	241	441	298		
	255	453	303		
	270	464	…		
	284	476	402		
	302	486	413		
		497	428		
		503	442		
		505	457		
			470		
			482		
			495		
			505		

Table 17. Video Camera Field Experiment Data.

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APPENDIX C. QR TACTICAL DECISION AID (TDA)

This Appendix discusses and describes the QR Tactical Decision Aid (TDA) which is being implemented for the use with QR codes. Work on this Decision Aid has been largely been done by Don Brutzman and Mike Bailey at the Naval Postgraduate School. The program is a desktop application, written in Java and in early stages of development. The QR TDA utilizes the Swing Graphic User Interface library and can be run headless which means that there is no Graphic User Interface required. In addition to the Swing library, additional Java libraries are used such as the QR code library known as the Google “zebra crossing” (zxing). “Pipes” is another Java library and is used as the dataflow library, which allows for the user to utilize the different tabs in the program. The TDA is basically broken up into two parts, sender and receiver. The sending side monitors a directory for new text files and when a new file is found and the program is running, it takes the file and goes through a series of steps to open, read, and encode the file before displaying a QR code on the screen. Once the QR code is displayed, the message is fired off to the receiver; the receiving side of the TDA monitors a predetermined directory, finds the message, reads the text, decodes the message and displays the proper QR code. If the TDA works correctly, identical QR codes will be displayed on either side of the program. The directory simulates an optical link between the two programs. The dataflow used in this program is component-based and externally configurable. Figure 76 is an image showing the sending side looking for and encoding a message found in the directory.

There are a few possible use cases for the QR TDA:

- QR TDA used during formation steaming allows quick and effective communication between multiple tactical units. This drastically reduces the time needed to encode and decode messages, which make tactical movements simpler to perform and reduces watch stander involvement in developing and decoding messages.

- When a message or tactical movement is required with short notice, the QR TDA can create the message and display the code effectively and efficiently.

Figure 76. Sending side of the Tactical Decision Aid watching a directory for new text files.

Figure 77 illustrates the sequencing process of the TDA. The basic operation behind this process is that the sender monitors a directory, finds the text file, and begins encoding the message. The sender breaks up the longer message into several smaller, more readable messages and adds a sequencing number to the message. The sequencing number ensures that the receiving unit is able to reassemble the message in the correct order even if the messages are not transmitted in order. As long as the sequencing numbers are correctly assigned, the receiving unit is able to reconstruct the original message. Figure 77 also illustrates the various tabs on the left side of the sender and the right side of the receiver, which is sort of a sequencing tool that is able to be utilized by the user. In addition to the existing tabs, encryption and decryption is a viable option in the future to enable the TDA to integrate security capabilities when developing and sending messages between tactical units.

Figure 77. Sequencing process of tactical decision aid illustrating both the sending and receiving capabilities of the TDA.

Figure 78 illustrates the longer message mentioned previously that is broken up into smaller messages and transmitted. This image also shows a string of "and" symbols, which indicates that there was an error in the message. This message was able to be broken up into smaller segments, encoded, and transmitted. Again, as long as the proper sequencing numbers are assigned to each individual QR code message, the receiver will be able to decode each message and reconstruct the original message.

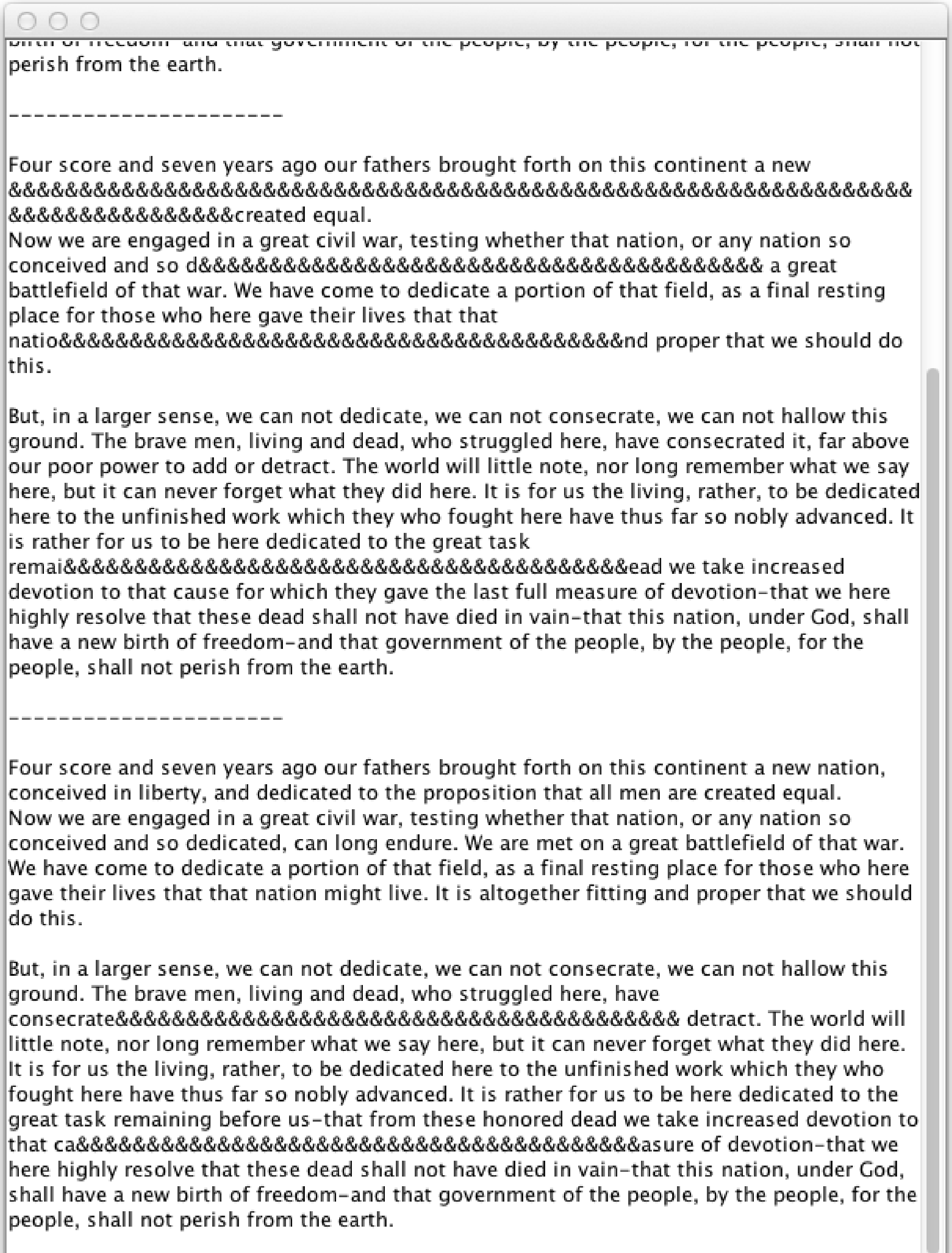

Figure 78. Image of the actual text to be detected, encoded, and displayed by the tactical decision aid.

The QR TDA is ultimately designed to allow war fighters operating in different tactical scenarios to be able to quickly and effectively write a message, encode the text in a QR code and fire the QR code off to another unit with the tactical signal. This is an additional tool to create an effective visual communication method to ensure that Emission Control is adhered to by all units when it is required. The vision of the Tactical Decision Aid is to be able to ultimately provide a point-to-point protocol connection between tactical units, which will allow them to communicate covertly and effectively.

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APPENDIX D. QR CODE WIKIPEDIA

> Wikipedia is an online open-content collaborative encyclopedia; that is, a voluntary association of individuals and groups working to develop a common resource of human knowledge. The structure of the project allows anyone with an Internet connection to alter its content. Please be advised that nothing found here has necessarily been reviewed by people with the expertise required to provide you with complete, accurate or reliable information.
>
> That is not to say that you will not find valuable and accurate information in Wikipedia; much of the time you will. However, Wikipedia cannot guarantee the validity of the information found here. The content of any given article may recently have been changed, vandalized or altered by someone whose opinion does not correspond with the state of knowledge in the relevant fields. (*Wikipedia*, n.d.)

The remainder of this appendix is taken directly from the QR Code Wikipedia page (http://en.wikipedia.org/wiki/QR_code, 14 May 2013). It is a non-standard reference and is included in the interest of completeness for the reader to understand the capabilities of QR code technology. By no means is this intended to be a de-facto reference for the development, implementation, or operation of an optical QR code communication system. It is provided here as a user reference.

QR code

QR code (abbreviated from **Quick Response Code**) is the trademark for a type of matrix barcode (or two-dimensional barcode) first designed for the automotive industry in Japan; a barcode is an optically machine-readable label that is attached to an item and that records information related to that item: The information encoded by a QR code may be made up of four standardized types ("modes") of data (numeric, alphanumeric, byte / binary, Kanji) or, through supported extensions, virtually any type of data.[]

QR code for the URL of the English Wikipedia Mobile main page, "*http://en.m.wikipedia.org*"

Recently,Wikipedia:Manual of Style/Dates and numbers#Chronological items the QR Code system has become popular outside the automotive industry due to its fast readability and greater storage capacity compared to standard UPC barcodes; applications include product tracking, item identification, time tracking, document management, general marketing, and much more.[]

A QR code consists of black modules (square dots) arranged in a square grid on a white background, which can be read by an imaging device (such as a camera) and processed using Reed-Solomon error correction until the image can be appropriately interpreted; data is then extracted from patterns present in both horizontal and vertical components of the image.[]

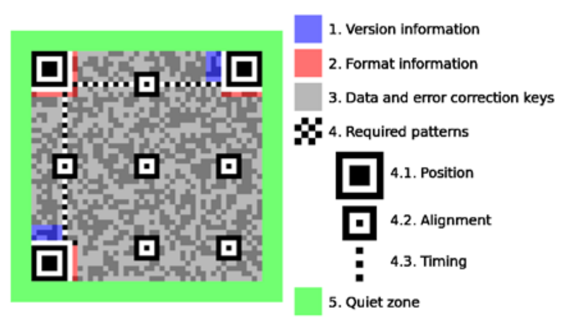
Telephone directory with QR code on the cover

Invention

The QR code system was invented in 1994 by Toyota's subsidiary, Denso Wave. Its purpose was to track vehicles during manufacture; it was designed to allow high-speed component scanning.[1] It has since become one of the most popular types of two-dimensional barcodes.[]

Standards

There are several standards that cover the encoding of data as QR codes:[]



- October 1997 – AIM (Association for Automatic Identification and Mobility) International[2]
- January 1999 – JIS X 0510
- June 2000 – ISO/IEC 18004:2000 *Information technology – Automatic identification and data capture techniques – Bar code symbology – QR code* [3] (now withdrawn)
  Defines QR code models 1 and 2 symbols.

- 1 September 2006 – ISO/IEC 18004:2006 *Information technology – Automatic identification and data capture techniques – QR code 2005 bar code symbology specification* [4]
  Defines QR code 2005 symbols, an extension of QR code model 2. Does not specify how to read QR code model 1 symbols, or require this for compliance.

At the application layer, there is some variation between most of the implementations. Japan's NTT DoCoMo has established de facto standards for the encoding of URLs, contact information, and several other data types.[5] The open-source "ZXing" project maintains a list of QR code data types.[6]

Uses

Originally designed for industrial uses, QR codes have become common in consumer advertising. Typically, a smartphone is used as a QR-code scanner, displaying the code and converting it to some useful form (such as a standard URL for a website, thereby obviating the need for a user to type it manually into a web browser).

"In the shopping industry, knowing what causes the consumers to be motivated when approaching products by the use of QR codes, advertisers and marketers can use the behavior of scanning to get consumers to buy, causing it to have the best impact on ad and marketing design."[7] As a result, the QR code has become a focus of advertising strategy, since it provides quick and effortless access to the brand's website.[8][9] Beyond mere convenience to the consumer, the importance of this capability is that it increases the conversion rate (that is, increases the chance that contact with the advertisement will convert to a sale), by coaxing qualified prospects further down the conversion funnel without any delay or effort, bringing the viewer to the advertiser's site immediately, where a longer and more targeted sales pitch may continue.

Although initially used to track parts in vehicle manufacturing, QR codes are now (as of 2012[10]) used over a much wider range of applications, including commercial tracking, entertainment and transport ticketing, product/loyalty marketing (examples: mobile couponing where a company's discounted and percent discount can be captured using a QR code decoder which is a mobile app, or storing a company's information such as address and related information alongside its alpha-numeric text data as can be seen in Yellow Pages directory), and in-store product labeling. It can also be used in storing personal information for use by government. An example of this is Philippines National Bureau of Investigation (NBI) where NBI clearances now come with a QR code. Many of these applications target mobile-phone users (via mobile tagging). Users may receive text, add a vCard contact to their device, open a Uniform Resource Identifier (URI), or compose an e-mail or text message after scanning QR codes. They can generate and print their own QR codes for others to scan and use by visiting one of several pay or free QR code-generating sites or apps. Google has a popular API to generate QR codes,[11] and apps for scanning QR codes can be found on nearly all smartphone devices.[12]

QR codes storing addresses and Uniform Resource Locators (URLs) may appear in magazines, on signs, on buses, on business cards, or on almost any object about which users might need information. Users with a camera phone equipped with the correct reader application can scan the image of the QR code to display text, contact information, connect to a wireless network, or open a web page in the telephone's browser. This act of linking from physical world objects is termed hardlinking or object hyperlinking. QR codes also may be linked to a location to track where a code has been scanned. Either the application that scans the QR code retrieves the geo information by using GPS and cell tower triangulation (aGPS) or the URL encoded in the QR code itself is associated with a location.[]

In June 2011, The Royal Dutch Mint (Koninklijke Nederlandse Munt) issued the world's first official coin with a QR code to celebrate the centennial of its current building and premises. The coin was able to be scanned by a smartphone and link to a special website with contents about the historical event and design of the coin.[14] In 2008, a Japanese stonemason announced plans to engrave QR codes on gravestones, allowing visitors to view information about the deceased, and family members to keep track of visits.[15]

QR codes have been used and printed on Chinese train tickets since 2010[13]

Mobile operating systems

QR codes can be used in Google's Android operating system and iOS devices (iPhone/iPod/iPad), as well as by using Google Goggles, 3rd party barcode scanners, and the Nintendo 3DS. The browser supports URL redirection, which allows QR codes to send metadata to existing applications on the device. mbarcode[16] is a QR code reader for the Maemo operating system. In Apple's iOS, a QR code reader is not natively included, but more than fifty paid and free apps are available with both the ability to scan the codes and hard-link to an external URL. Google Goggles is an example of one of many applications that can scan and hard-link URLs for iOS and Android. With BlackBerry devices, the App World application can natively scan QR codes and load any recognized Web URLs on the device's Web browser. Windows Phone 7.5 is able to scan QR codes through the Bing search app.

URLs

URLs aided marketing conversion rates even in the pre-smartphone era but during those years faced several limitations: ad viewers usually had to type the URL and often did not have a web browser in front of them at the moment they viewed the ad. The chances were high that they would forget to visit the site later, not bother to type a URL, or forget what URL to type. Friendly URLs decreased these risks but did not eliminate them. Some of these disadvantages to URL conversion rates are fading away now that smartphones are putting web access and voice recognition in constant reach. Thus an advert viewer need only reach for his or her phone and speak the URL, at the moment of ad contact, rather than remember to type it into a PC later.[]

Virtual stores

During the month of June 2011, according to one study, 14 million mobile users scanned a QR code or a barcode. Some 58% of those users scanned a QR or barcode from their homes, while 39% scanned from retail stores; 53% of the 14 million users were men between the ages of 18 and 34.[17] The use of QR codes for "virtual store" formats started in South Korea,[18] and Argentina,[19] but is currently expanding globally.[20] Big companies such as Walmart, Procter & Gamble and Woolworths have already adopted the Virtual Store concept.[21]

Code payments

QR codes can be used to store a bank account information or a credit card information, or they can be specifically designed to work with particular payment provider applications. There are several trial applications of QR code payments across the world.[22][23]

In November 2012, QR code payments were deployed on a larger scale in the Czech Republic when an open format for payment information exchange - a Short Payment Descriptor - was introduced and endorsed by the Czech Banking Association as the official local solution for QR payments.[24]

Website login

QR codes can be used to log in into websites: a QR Code is shown on the login page on a computer screen, and when a registered user scans it with a verified smartphone, they will automatically be logged in on the computer. Authentication is performed by the smartphone which contacts the server. A QR code login method called "Sesame" was trialled by Google in January 2012.[25]

Design

Unlike the older, one-dimensional barcode that was designed to be mechanically scanned by a narrow beam of light, a QR code is detected by a 2-dimensional digital image sensor and then digitally analyzed; the analyzer locates the three distinctive squares at the corners of the QR code, using a smaller square near the fourth corner to normalize the image for size, orientation, and angle of viewing. The small dots throughout the QR code are then converted to binary numbers and validated with an error-correcting code.

Storage

The amount of data that can be stored in the QR code symbol depends on the datatype (*mode*, or input character set), version (1, …, 40, indicating the overall dimensions of the symbol), and error correction level. The maximum storage capacities occur for 40-L symbols (version 40, error correction level L):[][26]

Maximum character storage capacity (40-L)

***character* refers to individual values of the input mode/datatype**

Input mode	max. characters	bits/char	possible characters, default encoding
Numeric only	7,089	3⅓	0, 1, 2, 3, 4, 5, 6, 7, 8, 9
Alphanumeric	4,296	5½	0–9, A–Z (upper-case only), space, $, %, *, +, -, ., /, :
Binary/byte	2,953	8	ISO 8859-1
Kanji/kana	1,817	13	Shift JIS X 0208

Here are some sample QR code symbols:

Version 1 (21×21). Content: "Ver1"

Version 2 (25×25). Content: "Version 2"

Version 3 (29×29). Content: "Version 3 QR code"

Version 4 (33×33). Content: "Version 4 QR code, up to 50 char"

Version 10 (57×57). Content: "Version 10 QR code, up to 174 char at H level, with 57x57 modules and plenty of error correction to go around. Note that there are additional tracking boxes"

Version 40 (177×177). Content: "Version 40 QR code can contain up to 1852 chars. (…)" (a total of 1,264 characters of ordinary/ASCII text, taken from an early version of this Wikipedia article)

Encryption

Encrypted QR codes, which are not very common, have a few implementations. An Android app,[27] for example, manages encryption and decryption of QR codes using the DES algorithm (56 bits).[28] The Japanese immigration system uses encrypted QR codes when issuing visa in passports [29] as shown in the figure here.

Japanese visa with a QR code

Error correction

Codewords are 8 bits long and use the Reed–Solomon error correction algorithm with four error correction levels. The higher the error correction level, the less storage capacity. The following table lists the approximate error correction capability at each of the four levels:

Damaged but still decodable QR code

Example of a QR code with artistic embellishment that will still scan correctly thanks to error correction.

Level L (Low)	7% of codewords can be restored.
Level M (Medium)	15% of codewords can be restored.
Level Q (Quartile)[30]	25% of codewords can be restored.
Level H (High)	30% of codewords can be restored.

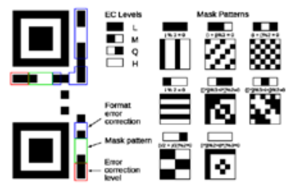
In larger QR symbols, the message is broken up into several Reed–Solomon code blocks. The block size is chosen so that at most 15 errors can be corrected in each block; this limits the complexity of the decoding algorithm. The code blocks are then interleaved together, making it less likely that localized damage to a QR symbol will overwhelm the capacity of any single block.

Thanks to error correction, it is possible to create artistic QR codes that still scan correctly, but contain intentional errors to make them more readable or attractive to the human eye, as well as to incorporate colors, logos, and other features into the QR code block.[31][32]

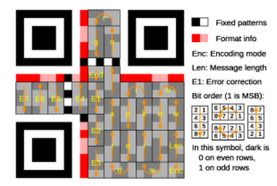
Encoding

The format information records two things: the error correction level and the mask pattern used for the symbol. Masking is used to break up patterns in the data area that might confuse a scanner, such as large blank areas or misleading features that look like the locator marks. The mask patterns are defined on a grid that is repeated as necessary to cover the whole symbol. Modules corresponding to the dark areas of the mask are inverted. The format information is protected from errors with a BCH code, and two complete copies are included in each QR symbol.[]

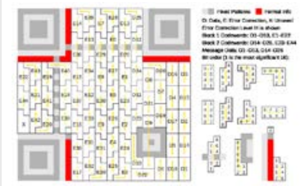
The message data is placed from right to left in a zigzag pattern, as shown below. In larger symbols, this is complicated by the presence of the alignment patterns and the use of multiple interleaved error-correction blocks.



Meaning of format information



Message placement within a QR symbol


Larger symbol illustrating interleaved blocks

Four-bit indicators are used to select the encoding mode and convey other information. Encoding modes can be mixed as needed within a QR symbol.

Encoding modes

Indicator	Meaning
0001	Numeric encoding (10 bits per 3 digits)
0010	Alphanumeric encoding (11 bits per 2 characters)
0100	Byte encoding (8 bits per character)
1000	Kanji encoding (13 bits per character)
0011	Structured append (used to split a message across multiple QR symbols)
0111	Extended Channel Interpretation (select alternate character set or encoding)
0101	FNC1 in first position (see Code 128 for more information)
1001	FNC1 in second position
0000	End of message

After every indicator that selects an encoding mode is a length field that tells how many characters are encoded in that mode. The number of bits in the length field depends on the encoding and the symbol version.

Number of bits per length field

Encoding	Ver. 1–9	10–26	27–40
Numeric	10	12	14
Alphanumeric	9	11	13
Byte	8	16	16
Kanji	8	10	12

Alphanumeric encoding mode stores a message more compactly than the byte mode can, but cannot store lower-case letters and has only a limited selection of punctuation marks, which are sufficient for most web addresses. Two characters are coded in an 11-bit value by this formula:

$$V = 45 \times C_1 + C_2$$

Alphanumeric character codes

Code	Character	Code	Character	Code	Character	Code	Character	Code	Character
00	0	09	9	18	I	27	R	36	SP
01	1	10	A	19	J	28	S	37	$
02	2	11	B	20	K	29	T	38	%
03	3	12	C	21	L	30	U	39	*
04	4	13	D	22	M	31	V	40	+
05	5	14	E	23	N	32	W	41	–
06	6	15	F	24	O	33	X	42	.
07	7	16	G	25	P	34	Y	43	/
08	8	17	H	26	Q	35	Z	44	:

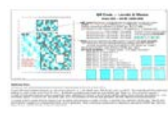
Decoding example

The following images offer more information about the QR code.


1 — Introduction


2 — Structure


3 — Layout & Encoding


4 — Levels & Masks


5 — Protocols

License

The use of QR codes is free of any license. The QR code is clearly defined and published as an ISO standard.

Denso Wave owns the patent rights on QR codes, but has chosen not to exercise them.[] In the USA, the granted QR code patent is US 5726435 [33], and in Japan JP 2938338 [34]. The European Patent Office granted patent "EPO 0672994" [35]. to Denso Wave, which was then validated into French, British, and German patents, all of which are still in force as of November 2011.

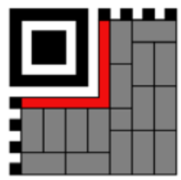
The word **QR code** itself is a registered trademark of Denso Wave Incorporated.[] In UK, the trademark is registered as E921775, the word "QR Code", with a filing date of 03/09/1998.[] The UK version of the trademark is based on the Kabushiki Kaisha Denso (DENSO CORPORATION) trademark, filed as Trademark 000921775, the word "QR Code", on 03/09/1998 and registered on 6/12/1999 with the European Union OHIM (Office for Harmonization in the Internal Market).[] The U.S. Trademark for the word "QR Code" is Trademark 2435991 and was filed on 29 September 1998 with an amended registration date of 13 March 2001, assigned to Denso Corporation.[]

Variants

Micro QR code is a smaller version of the QR code standard for applications with less ability to handle large scans. There are different forms of Micro QR codes as well. The highest of these can hold 35 numeric characters.[36]

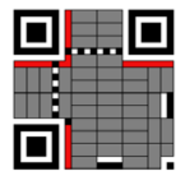
Model 1 QR code is an older version of the specification. It is visually similar to the widely-seen model 2 codes, but lacks alignment patterns.

Micro QR code example



Micro QR code functional regions

Model 1 QR code example



Model 1 QR code functional regions

Risks

Malicious QR codes combined with a permissive reader can put a computer's contents and user's privacy at risk. This practice is known as "attagging", a portmanteau of "attack tagging".[37] They are easily created and can be affixed over legitimate QR codes.[38] On a smartphone, the reader's permissions may allow use of the camera, full Internet access, read/write contact data, GPS, read browser history, read/write local storage, and global system changes.[39][40][41]

Risks include linking to dangerous web sites with browser exploits, enabling the microphone/camera/GPS, and then streaming those feeds to a remote server, analysis of sensitive data (passwords, files, contacts, transactions),[42] and sending email/SMS/IM messages or DDOS packets as part of a botnet, corrupting privacy settings, stealing identity,[43] and even containing malicious logic themselves such as JavaScript [44] or a virus.[45][46] These actions could occur in the background while the user is only seeing the reader opening a seemingly harmless web page.[47] In Russia, a malicious QR code caused phones that scanned it to send premium texts at a fee of US$6 each.[37]

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[37] .
[46] QR Codes hold up to 2.9 KB whereas the smallest known computer virus is about one-tenth that size

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External links

- Official website (http://www.qrcode.com/en/index.html)
- Reed Solomon Codes for Coders (http://en.wikiversity.org/wiki/Reedâ Solomon_codes_for_coders) – an elaborate tutorial on Wikiversity, covering both QR code structure and the Reed Solomon codes used to encode the data.
- J. D. Biersdorfer (2 March 2011). "Q&A: how to Make a Quick Response Code" (http://www.nytimes.com/2011/03/03/technology/personaltech/03askk.html). *The New York Times*. Retrieved 11 December 2012. Information on converting a URL into a QR code

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