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ENABLING ROBOTIC TELEMEDICINE CAPABILITIES IN AUSTERE ENVIRONMENTS

by

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Preservation of the life of combat casualties is the premier responsibility of U.S. military health services. With advancing warfighting capabilities, the theater in which battles are fought has transcended a plethora of austere environments, thus creating the implicit need to advance lifesaving medical capabilities and ensure the highest level of health care possible. Static medical treatment facilities have employed telemedical capabilities in the form of precise, remotely controlled robotics to extend not only the distance of which health care can be given, but also reduce the time in which specialized care can be rendered. Robotic surgeries are performed by medical providers who are dependent on secured network capabilities to provide the best connectivity and response available during these sensitive procedures. The networking ability to support telemedicine and telesurgeries is important because it will determine where and how robotic surgeries can be utilized. This thesis will examine control of telemedicine surgical capabilities of the Taurus-M type, which are capable of supporting real-time delay and accuracy-sensitive telesurgery operations, but require robust, fast-response networking capabilities. This research will aid in beginning to understand how anticipated network degradation in austere environments limits the ability to perform tasks and serve as a force multiplier in military medicine.

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ENABLING ROBOTIC TELEMEDICINE CAPABILITIES IN AUSTERE ENVIRONMENTS

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ABSTRACT

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LIST OF ACRONYMS AND ABBREVIATIONS

2E	2 Expanded
AESOP	automated endoscopic system of optimal positioning
AKI	acute kidney injury
AO	area of operation
AMEDD	Army Medical Department
ARPANET	Advanced Research Projects Agency Network
BAS	battalion aid station
BUMED	Bureau of Medicine and Surgery
BVM	bag valve mask
C3T	command, control, communications tactical
CASEVAC	casualty evacuation
CCRN	critical care registered nurse
CLS	Combat Lifesaver
CSH	combat surgical hospital
CT	computerized tomography
CONUS	continental United States
COSC	combat and operational stress control
CRADA	cooperative research and development agreement
DARPA	Defense Advanced Research Agency
DCR	damage control resuscitation
DNBI	disease and non-battle injury
DOD	Department of Defense
DODIN	Department of Defense information network
DON	Department of the Navy
DOW	died of wounds
EMF	expeditionary medical facility
EMT	emergency medical technician
ERCS	en route care system
FDA	Food and Drug Administration
FMST	field medical service technician
FRSS	forward resuscitative surgical system

FRSD	forward resuscitative and surgical detachment
HM	hospital corpsman
HMD	head-mounted display
HSS	health services support
ICU	intensive care unit
LOC	lines of communication
MRI	magnetic resonance imaging
MANET	mobile ad-hoc networks
MEDEVAC	medical evacuation
MEO	medium earth orbit
MMU	multinational medical unit
MTF	military treatment facility
NATO	North Atlantic Treaty Organization
NCTI	non-compressible torso injuries
OEF	Operation Enduring Freedom
OIF	Operation Iraqi Freedom
OCU	Operator control unit
POI	point of injury
PPD	patients per day
PROBOT	prostate robot
PUMA	programmable universal machine for assembly
RTP	real-time transport protocol
RAS	robotic-assisted surgery
RMIS	robotic minimally invasive surgery
SARP	surgeon-assistant robot for prostatectomy
SATNET	Atlantic packet satellite network
SGA	supraglottic airway
STP	shock trauma platoon
TATRC	Telemedicine and Advanced Technology Research Center
UDP	user datagram protocol
USA	United States Army
USN	United States Navy

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I. INTRODUCTION

Early casualty combat care within the Navy and Marine Corps team remains fundamentally straightforward. This process involves initial life sustaining care at the point of threat to health, continuous to triage, proactive and situational treatment dictated by casualty status, and expedited transport to the appropriate echelon of care. However, to further delve through the gamut of the concept of casualty care, complexities are made evident from the layers of factors presented by the chaos of combat. Such complexities include - varying trauma mechanisms; varying levels of medical expertise of medical teams or first responders; terrain and environmental challenges; and limited communication to specialists at higher levels of care. The latter challenge will be the focal point of this project as we explore advanced tactical network methodologies as potential mitigating factors in future combat settings.

High quality care, medical innovations, and time in the combat casualty environment all weigh heavily when saving lives. The U.S. Joint Chiefs of Staff define varying levels of medical care in Joint Publication 4-02, Joint Health Services (2017). These echelons of care are ordinally named Roles 1 through 4. Role 1, known under a variety of names such as *first responder care*, *combat lifesaver*, *unit-level care,* and *self-aid / buddy-aid,* focuses on urgent, lifesaving treatment to those who have sustained life threating injuries, routine non-combat related treatment, and a variety of other services not requiring a specialty care (Joint Chiefs of Staff, 2018). Role 2 provides forward resuscitative care (FRC) continuation and damage control procedures to stabilize the patient for transport to a facility that, if necessary, can provide advanced medical care (Joint Chiefs of Staff, 2018). Role 3 facilities provide, stable, in-theater hospitalization with a dedicated bed capacity after specialty care is rendered (Joint Chiefs of Staff, 2018). Lastly, Role 4 care, located in the U.S. or at designated overseas facilities, provide definitive and rehabilitative care outside the area of combat operations (Joint Chiefs of Staff, 2018).

Table 1. Description of roles of military medical care

Roles of Medical Care	Description of Care Provided
Role 1 – First responder, self-aid / buddy-aid, unit-level care	Immediate life-saving care, treat disease and non-battle injuries, combat stress prevention, tactical combat casualty care, and routine illness treatment (Headquarters, Department of the Army, 2020)
Role 2 – Forward resuscitative care	Advanced trauma management, resuscitative care, damage control surgery, and a variety of ancillary services to aid in sustaining life until evacuation is to a higher level of care is available (Joint Chiefs of Staff, 2018)
Role 3 – Theater hospitalization	Continuation of Role 2 specialty care, postoperative care, and non-combat related routine care (Joint Chiefs of Staff, 2018)
Role4 – Definitive Care	Comprehensive medical and surgical care (*Health Service Support Field Reference Guide - MCRP 3-40A.5*, 2018)

Known as the "golden hour," medical personnel put a premium on the evacuation time as a valuable barometer to the medical team's ability to sustain life (Childers & Parker, 2017). Although evacuation times have drastically dropped to around 55 minutes across varying military casualty care systems (Gerhardt et al., 2011), medical planners will continue to strive to not only improve on these measures, but to improve on overall delivery of care. This can be achieved through employing innovative clinical high-end networking and remotely controlled robotic tools that will improve upon casualty care delivery in the interim periods when access to specialty care is not available.

Robotic assisted surgery has been around since the turn of the 21st century and has greatly enhanced a surgeon's ability to perform procedures. The da Vinci system by Intuitive has three separate components including the surgeon console, patient cart, and a vision cart. It has evolved through four generations of units and through the use of a clutch at the surgeon console, has the ability to rotate 360 degrees without having to regrip an instrument, thereby giving a surgeon greatly improved range of motion and dexterity. This system is extremely capable and has performed over 6 million procedures all across the world, however it is designed as a stationary system that is tied to a specific operating room and hospital ("Da Vinci Surgery | Da Vinci Surgical System | Robotic Technology," n.d.).

By scaling down the da Vinci system, SRI International has created the Taurus robot, which can be transported and installed at remote locations across the world. Tom Low, the director of robotics at SRI, highlights Taurus components and capabilities.(Low, n.d.) It has a high-definition camera mounted on it and two robotic arms that can use da Vinci instruments and provide the continuous rolling motion with haptic feedback available to provide the "feel" a surgeon requires. This compact, lightweight version of a commercially proven platform requires further exploration into its capabilities and requirements to enable telemedicine in austere environments.

When Navy Hospital Corpsman (HM), Marines, or Army Medics are charged with location, collection, initial care, and preventive care, they do so independently (Gerhardt et al., 2011). Limited consultation may be achieved through radio communication, but this medium can be enhanced with visual or real-time data communication allowing off-site specialist real-time visual or vital signs assessment capabilities. This would multiply advanced medical (trauma surgeons, advanced registered nurses, physician's assistants, or specialists stationed in remote locations) capabilities and project their expertise directly on to the battlefield.

Within a more controlled clinical environment, telemedicine can take an approach towards a more precise application with the virtual reality-controlled Taurus system. Realistic early stages of application in the combat casualty environment would be direct surgery assistance as an automated tool changing, supply unpackaging, dispensing, disposal, and tracking. Diagnostically, Taurus could potentially add capabilities involved with patient scanning and remote assessment and preoperative CT registration and navigation.

In combat medicine, problems will always revolve around constant improvement of caring for the most valued assets, sailors and marines. In this specific case, however, the problem lies in successful and, more importantly, the safe deployment of these telemedicine options within the combat casualty environment. This hinges squarely on the operability within a tactical wireless system. Exploration of viable network topology, technology and methodology must be considered upon deployment of telemedicine within this setting.

We envision an operational scenario where a ground force is deployed within an immanent hazardous area where missions are conducted up to several hundred miles away from a stabilized, medical facility and exponentially further from a medical treatment facility that can provide definitive and rehabilitative care. More specifically, the point where a military member sustains a combat injury is within an urban setting, located 100 miles from the closest medical facility that can provide trauma-level care. Additionally, immediately outside the city is mountainous terrain that can be traversed by ground vehicle or rotary wing aerial transportation.

In the event that a simultaneous mass casualty has overwhelmed medical capabilities of the personnel, supplies, and/or equipment, a trauma surgeon located in a medical facility that provides definitive care, can observe a live, audio-video stream and provide medical support coverage for the indisposed surgeons and personnel physically aiding the mass casualty. This cooperative assessment and triage of the patient will play a vital role for the next decisions that the Role 2 trauma team will make. The provider manipulating the Taurus system throughout the surgical case will be located at a Role 4 facility providing support in the form of patient evaluation and surgical assistance to the on-site surgeon.

A. PROBLEM STATEMENT

Role 2 medical facilities lack the flexibility to sustain a high degree of medical effectiveness during events in which several simultaneous casualties arrive that exceed the available capabilities, typically personnel; commonly referred to as a mass casualty (Brennan, n.d.). During a mass casualty, medical personnel such as trauma surgeons, anesthesiologists, trauma nurses, and surgical technicians are required to triage and attend to multiple combat injuries that require immediate surgery and stabilization in order to be medically evacuated to a Role 3 or 4 level of care. The preparation, monitoring, and closing of a surgical case requires the full attentiveness of each medical professional, thus a mass casualty occupies available personnel's capabilities and limits coordination of casualty care to one case at a time.

B. PURPOSE

The purpose of this research is to expand the body of knowledge regarding the emerging robotic telemedicine capabilities. Specifically, we are interested in the commercially available Taurus-M robot and how that system performs under various network conditions (International, 2020). This will give the Navy, Army, and Air Force operational medicine planners current and relevant information to consider when examining Role 2 facilities capabilities and limitations in mass casualty events. The ability to use robotic telemedicine as a force multiplier could provide a unique opportunity to save lives without significantly impacting personnel requirements. The potential benefits of deploying this emerging technology to austere operating environments instead of increasing manpower or accepting the risk of resources being overwhelmed in mass casualty scenarios, is worth further examination. This study will delve into the remote telemedicine capabilities of Taurus and begin to understand how network degradation, which is anticipated in austere environments, limit its ability to perform tasks and serve as a force multiplier. Additionally, through literature analysis, this study will contribute to the capabilities body of knowledge for telemedicine and telesurgery connectivity in austere, combat environments; an area of study that has not been studied nor developed.

C. SCOPE AND LIMITATIONS

The potential benefits from this study are an increased understanding of commercially available robotic telemedicine capabilities, further insight into the networking requirements to support this emerging capability, continued partnership with the premier organization of SRI International, collaboration with multiple elite institutions who are interested in similar applications of the Taurus robot. Limitations include the COVID-19 environment and corresponding restrictions of face-to-face meetings, which hampers the ability to fully collaborate and lengthens overall processes. Potential recommendations could include minimum networking requirements and expected degradations of the associated robotic telemedicine capabilities.

D. RESEARCH QUESTIONS

How do the telemedicine requirements for these emergent surgical robotic capabilities reveal themselves?

- What are the minimum operational network requirements to remotely support Taurus capabilities?
  - Haptic feedback latency minimums
  - High-definition VR goggle minimums
  - Degradation levels of Taurus capabilities
- Given a battlefield combat injury, how does network degradation impact operations at the Role 2 and what are some potential responses to mitigate the impact?
- What are the major constraints of current in-theater network infrastructure capabilities that will limit the Taurus' operational capabilities?

The dynamic nature of warfighting is inundated with calculated risks with the intent to successfully defeat a belligerent (Clausewitz et al., 1989). Clausewitz et al. (1989) defined war as "an act of violence intended to compel our opponent to fulfil our will." Inevitably, people who are the recipients of these acts will suffer traumatic, life-threatening injuries and will need immediate medical intervention to preserve their life. With the establishment and advancement of U.S. military medical treatment in the battlefield coupled with technologically superior healthcare capabilities, the future of lifesaving treatment in austere battlefield environments has the potential of being highly successful. Just as warfare strategy and methodology, through the centuries, has changed with the purpose of expanding its efficaciousness and lethality, so has medical care in providing lifesaving procedures as close to the point of injury (POI) to minimize the time before being treated. Over the last two decades, military engagements in the middle east have been medically serviced by deploying various levels of trauma-level medical care as close to the forefront of combat. Exceeding the medical capabilities of Roles 1 and 2, both physical and skill limitations of providers, there is an observable need to increase both factors to ensure that the appropriate type of care is quickly available when the time arises. By understanding the functions and capabilities of doctrinal military medical care and robotic assisted medical devices, we can discern the possibility of interoperability and shape the future battlefield medical care .

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II. LITERATURE REVIEW

A. MEDICAL FACILITY ROLES AND CAPABILITIES IN DOD

As one of the Joint Warfighting Functions, sustainment, is one of the primary logistics services, in addition to personnel support, that support continuing operations though mission completion and any redeployment of personnel forces and necessary provisions (Deployable Training Division, 2018). Sustainment functions provide details that bolster initial supply and replenishment, maintenance, logistics services, engineering, operational contract support, and health services support. To aid personnel in human resource, financial, and religious matters, the Sustainment function includes the assets necessary to carry out those capabilities (Deployable Training Division, 2018). Present day battlefield environments are riddled with multifaceted challenges that can degrade the force's ability to provide and receive proper sustainment capabilities needed to be operationally capable and execute a mission. Disruption of sea and air lines of communication (LOCs), global provider availability, and cyber network vulnerabilities are just a few of the notable challenges a JFC must overcome to guarantee an effective continuation of the Sustainment function (Joint Chiefs of Staff, 2018).

To effectively sustain mission operations, the Sustainment function not only transcends the ability to mitigate deterrence challenges but must ensure that all personnel are receiving the provisions at the basic unit level. Health services support (HSS) in operational environments relies heavily on providing basic life-saving provisions from the point of injury to definitive care, removed from the operational environment (Headquarters, Department of the Army, 2020).

All branches of the U.S. military must subscribe to the Joint Publication, 4–02, Joint Health Services (Joint Chiefs of Staff, 2018), when developing plans and activities for joint operations. Though all branches have a responsibility in delivering health services support, the vast majority of the joint operational care when conducting military ground operations is provided by the U.S. Navy (USN) and U.S. Army (USA). All branches' adherence to the JP 4-02 allows for a disambiguation of health services during joint operations, thus providing shared medical capabilities for the force. These capabilities are supported under the doctrine of the U.S. joint functions ‘sustainment’ and ‘protection,’ which are colloquially referred to as Health Support Services and Force Health Protection, respectively.

1. Role 1

The immediate role of medical care that military personnel receive is at this level. A wide-breadth of care is classified under this role and is classified, in non-battle situations, as unit-level care. Apart from actions that contribute to directly preserving life, there are several other medical need that are addressed. This includes:

a. Disease and Non-Battle Injuries (DNBI)

DNBI inhibit personnel from executing their functional requirements and duties. Such injuries that are identified can include dermatologic, gastrointestinal, psychiatric, neurological, and several other categories that affect personnel body systems (Belmont et al., 2010).

b. Combat and Operational Stress Control (COSC)

COSC in a Role 1 setting include treatments that respond to the physiological and psychological injuries to military personnel during combat situations. Some of these injuries include trauma from the loss of a fellow unit member, child combat fatalities, and performing prolonged medical treatment of combat casualties. Treatment for these injuries include emotional regulation and compartmentalization, group therapy, and coping skills education (Campbell et al., 2019).

c. Patient Location and Collection

Patient location and collection points are established for consolidated evacuation to higher echelons of care. A singular location associated with battalion aid stations (BAS) provides a consolidated, easily accessible area to support patient movement (Headquarters, Department of the Army, 2020).

d. Combat Life-Saving Actions

Immediate life-saving actions to preserve life and the ability to get the casualty to the next level of care. This type of treatment is commonly performed by trained combat medics or corpsmen. These actions after injury include preserving airways, tourniquet placement, and other stabilizing practices ("Combat Lifesaver / Tactical Combat Casualty Care Student Handout," 2017).

To support the effective execution of these critical responsibilities, personnel are trained in a varietal level of medical care. The most basic care for any member is referred to as self-aid and buddy aid. Members are trained that in the event of sustaining an injury to oneself or a fellow member, to perform aid that will increase the likelihood of survival. The first-aid techniques may be broadened depending on the area of operation in which the injury occurred. For example, personnel may be trained in additional chemical warfare treatment when conducting operations in areas known for such incidents (Joint Chiefs of Staff, 2018).

Additional training can be given to designated personnel whose primary occupational code is non-medical. This training, Combat Lifesaver (CLS), provides these members with a capability skillset beyond that of buddy aid. This designation is normally assigned to personnel members whose primary occupation involves medical care and are assigned to an operational unit. But, if such medical personnel are unavailable, other member(s) are trained to perform Combat Lifesaver techniques when needed, along with their primary occupational duties. In many instances when these techniques are needed to be set in motion are under duress in a combat situation, thus elevating a member's duty to provide CLS immediately after suppressing the enemy (Flynn, 2014). Additional measures performed by CLS-trained members include managing penetrating chest wounds, splinting broken bones, and administering medications ("Combat Lifesaver / Tactical Combat Casualty Care Student Handout," 2017).

Primary occupation medical personnel are also available at the Role 1 level to provide basic sick call and treat minor medical needs in which personnel can recover from quickly and return to duty. A variety of medical specialties may be employed, such as independent duty corpsmen, expeditionary combat medics, and physician assistants. With the specialized expertise these members have, come less trivial responsibilities such as casualty evacuation coordination, mass casualty triage, and resuscitative care ("Health Service Support Field Reference Guide – MCRP 3-40A.5," 2018).

2. Role 2

Role 2 medical care is the continuation of lifesaving treatment to ensure emergent care is provided using advanced procedures and capabilities. These capabilities, though, do not include definitive care to which a casualty can return to duty. There is an implicit focus for Role 2 personnel to maintain an airway, stop the bleeding, and evacuate the patient to the next echelon of care. Strict adherence to the immediate prevention and mitigation of permanent, physical damage focuses on damage control resuscitation and surgery (Joint Chiefs of Staff, 2018).

Resuscitative intervention and damage control surgery efforts include:

- Controlling spontaneous hemorrhages with a variety of hemostatic agents
- Managing decreased blood pressure levels through permissive hypotensive resuscitation
- Controlling hypovolemia, the rapid loss of plasma, by replacing circulating warm blood
- Immediate amputation of unrecoverable limbs
- Decompressive craniectomy to control the rapid swelling of brain tissue
- Addressing acute compartment syndrome by performing fasciotomies on internally hemorrhaging muscles
- Controlling internal bleeding through laparotomic procedures
- Sourcing and managing internal bleeding from penetrating chest wounds by performing a thoracotomy

The expanded ability to surgically resuscitate casualties, with the goal of getting to the next level of care, is aided by increasing critical medical capabilities. Additional capabilities include laboratory services, X-ray, dental, preventative medicine, and packed blood products. Although definitive care bed capacity is not available, there is a limited capacity to hold patients to be evacuated to the next assigned level of medical care.

3. Role 2 Light Maneuver (Role 2LM)

As a highly mobile and versatile land or afloat asset, Role 2LM can perform resuscitative care and airway management procedures such as cricothyrotomies, bag valve mask (BVM) ventilation, and supraglottic airway (SGA) placement (Dye et al., 2020). The limiting responsibility of Role 2LM is damage control surgery due to injuries that threaten the life, limb, or eyesight of the casualty. Subsequently, once pos-surgery stabilization is achieved, the patient will be moved to a Role 2 Enhanced (E) or Role 3 facility ("Health Service Support Field Reference Guide – MCRP 3-40A.5," 2018).

4. Role 2E

With an expanded capability set, Role 2E facilities can achieve patient stabilization that can omit the need to evacuate the patient to a Role 3. Rather, the patient is able to directly proceed to a Role 4 facility for definitive care. Role 2E facilities are outfitted with an intensive care unit (ICU), limited dental care, preventative medicine measures, operational stress control supervision, and ancillary services such as laboratory and X-ray.

Both, the Navy's Forward Resuscitative Surgical System (FRSS) and the Army's Forward Resuscitative and Surgical Detachment's (FRSD) personnel's leading mission is to carry out the actions needed during emergency resuscitative care and damage control surgery (Headquarters, Department of the Army, 2020). The small logistical footprint coupled with their quickly deployable nature, enables early intervention and mobility into, and throughout, the AO.

A Navy FRSS is structured within a surgical platoon, overall commanded by a headquarters section of a surgical company ("Health Service Support Field Reference Guide – MCRP 3-40A.5," 2018). To aid the FRSS in the care of trauma patients, a surgical company is augmented with limited radiological capabilities, a laboratory section, en- route care, casualty collection, and evacuation via shock trauma platoons (STP). Given a full complement of medical materiel and staffing, a FRSS can treat up to eighteen patients within forty-eight hours until needing a resupply and rotation of medical staff ("Health Service Support Field Reference Guide – MCRP 3-40A.5," 2018). The patient care capability of a FRSS can sustain two preoperative patients, one intraoperative patient, and two postoperative patients at one time ("Health Service Support Field Reference Guide – MCRP 3-40A.5," 2018). The duration to hold a patient until evacuation, though, is limited to four hours. Patients must be stabilized and tended to by the en-route care team while casualty evacuation (CASEVAC) and patient movement can be coordinated with the next, higher echelon of medical care ("Health Service Support Field Reference Guide – MCRP 3-40A.5," 2018).

Since a FRSS is very mobile and does not need external support to transport its materiel, it can be fully operational capable within one hour and broken down, ready for transport again within the same amount of time. Supporting accompaniment such as personnel, power generators, and shelter are transported over ground within USMC M997 and M998 tactical vehicles, and M101A trailers ("Health Service Support Field Reference Guide – MCRP 3-40A.5," 2018).

Personnel composition to operate a FRSS include ("Health Service Support Field Reference Guide – MCRP 3-40A.5," 2018):

- two emergency medicine surgeons
- one anesthesiologist
- one to two critical care nurse(s)
- three operating room technicians
- one independent duty corpsman

Anesthesiologists can be augmented with a certified registered nurse anesthetist, bringing the total personnel number between eight and ten.

Army FRSDs are equipped with a greater number of personnel and materiel sustainment compared to that of a Navy FRSS. This gives the FRSD the ability to operate as a full complement detachment or task organize as multiple forward resuscitative and surgical sections (Headquarters, Department of the Army, 2020).

Its primary mission is to stabilize patients in preparation for any needed urgent surgical treatment, perform permissive hypotensive resuscitation, and assist with ongoing care of the patient until evacuation to the next echelon of care is possible. The resuscitative section is comprised of (Headquarters, Department of the Army, 2020):

- two emergency medicine physicians
- two emergency care nurses
- two emergency care sergeants

In situations where patients must advance to a surgical section, personnel are tasked to perform damage control surgery, burn management, advanced resuscitative procedures and airway management, central line placement, intravenous infusions, and pain management. Subsequent monitoring and care are performed until the patient can be evacuated to the next echelon of medical care. Given the extended responsibilities within the surgical section, increased number and variety of personnel is required to ensure appropriate care (Headquarters, Department of the Army, 2020):

- two general surgeons
- two orthopedic surgeons
- two critical care nurses
- two certified registered nurse anesthetists
- one operating room non-commissioned officer
- one operating room sergeant
- one practical nursing specialist

From point of injury to definitive care, en route care is an essential part of maintaining continuous care to improve survivability outcomes. The system works to ensure the mode of conveyance is the best suited when considering the patient's destination for medical care ("Health Service Support Field Reference Guide – MCRP 3-40A.5," 2018). Additionally, it reduces the need for more medical personnel to be operationally forward. This allows for long-term care to be in an area away from battlefield operations or completely out of the area of operations, thus reducing the risk of injury to a greater number of medical providers. Throughout the patient movement process from Roles 2, 3, and 4, stabilization is a prerequisite prior to departure and paramount during movement since rapid physiological changes can destabilize the patient and cause serious injury or death. En route care supplies and equipment must be able to integrate within the aircraft, ambulance, or vessel that is being used to transport the patient. Equipment with a broader range of capability, smaller, and lighter in weight is ideal when considering the fuel range, availability, and space within the mode of transportation ("Health Service Support Field Reference Guide – MCRP 3-40A.5," 2018).

The USMC ERCS is comprised of one Field Medical Service Technician (FMST) and one critical care nurse. The team can support two critically injured patients for up to two hours with medium lift, operationally approved aircraft for a distance of up to 240 nautical miles ("Health Service Support Field Reference Guide – MCRP 3-40A.5," 2018). Other patients categorized as needing less urgent or routine care can be outfitted into aircraft that can support much longer durations of care en route.

5. Role 3

Role 3 medical care is performed within theater hospitals or military treatment facilities (MTF). The care capabilities provided within a theater hospital are designed to handle and exceed that of a Role 1 or 2. Role 3 MTFs that are geographically located within or near the AO allow for patients that are not able to safely make the journey to definitive, CONUS care with a wide range of treatment. Additionally, Role 3 facilities treat patients that can return to duty within the AO. Role 3 care includes (Joint Chiefs of Staff, 2018):

- postoperative care
- inpatient and outpatient care
- enhanced diagnostic capabilities
- greater amount of medical materiel to support a wide breadth of surgical procedures, including maxillofacial and neurological
- additional capabilities within ancillary services such as pharmacy, laboratory, and radiological diagnostics
- gynecological and obstetric services
- cardiology
- optometry and ophthalmology
- behavioral and occupational health
- advanced dental facilities
- medical logistics
- veterinary care

Role 3 MTFs can be established within a variety of structures. For example, the U.S. Navy's Expeditionary Medical Facility (EMF) Djibouti, located aboard Camp Lemonnier, Djibouti. As well as, the North Atlantic Treaty Organization (NATO) Role 3 Multinational Medical Unit (MMU) located on the Kandahar Airfield in Kandahar, Afghanistan. Both of these Role 3 facilities are constructed as fixed, brick and mortar structures. But MTFs are not limited to brick and mortar or statically located structures. The Army Medical Department's (AMEDD) combat support hospitals (CSH) are modularly structured by using climate-controlled tents constructed on terrain that has been cleared and graded by civil engineers (Headquarters, Department of the Army, 2020). The U.S. Navy currently has two hospital ships, the USNHS Comfort and USNHS Mercy.

These afloat facilities are outfitted with the same capabilities as their land-based counterparts (Joint Chiefs of Staff, 2018).

6. Role 4

Patients that cannot physically return to duty within the AO are transported to an MTF that can provide definitive care and rehabilitation, if necessary. These facilities that can provide Role 4 care are located within the continental U.S. (CONUS) and approved military, overseas facilities that can provide expanded care. Role 4 facilities must meet civilian medical standards in providing comprehensive medical care (Joint Chiefs of Staff, 2018).

B. CASUALTY CARE IN AUSTERE ENVIRONMENTS

What is the recent data and how have units been successful in the past? Where did the capabilities fall short?

As Kowat el al. (2018) found and further substantiated through constant development of military medicine doctrine, Roles 1 through 3 in austere environments are crucial components when saving lives afflicted by battle. Effective training, adequately providing physical and personnel resources, and refining lessons learned over the past centuries of documented medical treatment during battle has led to increased survivability outcomes. Adapting proven medical advancements as close to the POI could increase the survivability rate of current and future military engagements (Kotwal, Staudt, Trevino et al., 2018). Despite the high chances of survival when injured, the potential to prevent death through medical intervention still exists.

The continuity of care from pre to post damage control surgery provided by a singular CCRN proved beneficial through en route care support when patients were transported from Role 2 to Role 3 medical facilities. Additionally, forward resuscitative surgical systems were staffed with CCRNs that were organic assets to the Role 3 EMF and designated for any immediate need of an ERC team. This seamless handoff from surgery to ERC CCRNs freed organic FRSS medical personnel to treat the next surgical case (MCRP 3-40A.5).

During the middle engagement years in Afghanistan, 2008–2014, Role 2 facilities were documented to have treated nearly 10,000 casualties with an over 95% survivability rate up to the next echelon of care. A vast majority, 90.9%, of fatalities were the corollary of hemorrhage trauma, with 80.1% classified as "potentially survivable" (Kotwal, Staudt, Mazuchowski et al., 2018). These results underscore the necessity of reducing the time; increasing the capability at a Role 2; or both, in getting lifesaving, hemorrhagic care.

Kowat et al. (2018) found of the recorded Role 2 fatalities that were transported to a Role 3 facility in Afghanistan from 2008–2014, the majority (nearly 62%) had begun their evacuation within one hour of determining the need for greater, lifesaving capabilities, with a median time of 53 minutes.

As Cai et al. (2018) found, that during the Operations Enduring Freedom (OEF) and Iraqi Freedom (OIF), no medical treatment advantages that substantiated the use of FSTs with teams of twenty medical personnel over smaller teams of eight to ten. Rather, given the large percentage of soft tissue and orthopedic injuries, 41.0% and 31.6%, respectively, a greater number of orthopedic surgery capabilities should be employed (Cai et al., 2018).

During the early stages of OEF and OIF, forwards deployed surgical systems, FSTs and FRSSs, were effective in providing immediate, battlefield trauma care that resulted in a decrease of morbidity rates among warfighters (Childers & Parker, 2017). As these operations matured and the establishment of Role 3 facilities such as Joint Forces Medical Group Role 3 Hospital Camp Bastion, Afghanistan, Role 2 facilities saw fewer patients per day (PPD). In large part, this was due to the direct evacuation from the POI to a Role 3 facility that provided immediate, superior medical resources. Furthermore, subsequent battlefield trauma casualty treated at an FST or FRSS after the establishment of an AO Role 3, saw an increase in their morbidity rate because of the lack of advanced medical care providers or capabilities (Childers & Parker, 2017).

Although, Reade and Brennan (2017) made dichotomic position on usefulness of Role 2, particularly Role 2E, facilities. Such that, patient outcomes were markedly favorable when receiving care from a Role 2-type facility in environments where admissions averaged over 50 per month. Suggesting that provider competency levels were higher because of this. Nevertheless, it was underscored that there is, and will continue to exist, the need for specialized trauma care in austere environments (Reade & Brennan, 2017).

Amputation and non-compressible torso injuries (NCTI) were commonly observed results of the injuries sustained during combat. At a time in which nearly 90% of combat mortalities happened prior to arrival at a Role 2 or 3 facility, it was morbidly clear to see that medical evacuation (MEDEVAC) time was a crucial factor when treating NCTIs that carried a mortality rate of over 85%. Together, patients who sustained an extremity amputation, an NCTI, and MEDEVAC transit times greater than 60 minutes, accounted for 16.7% of the combat trauma mortality rate (Maddry et al., 2018). As Maddry et al. (2018) go on to explain, MEDEVAC time (classified as: less than 30 minutes; between 30 and up to 60 minutes; and greater than 60 minutes) was proportional to the mortality rate when casualties suffered amputations and an NCTI. Such that, the lower the MEDEVAC time the greater the chance of survivability among that patient population.

From the early buildup of conflict during OEF and, subsequently, through 2011 to the close of OIF, over 57,000 U.S. Army soldiers suffered trauma injuries and were treated at Role 2 and Role 3 facilities (Langan et al., 2014). From 2002 until 2006, the Joint Theater Trauma Registry recorded a statistically significant increase in the percentage of soldiers that died of wounds (DOW) from traumatic injuries. Attention was given to this trend and by the end of 2005, U.S. military medicine implemented a marked revision of damage control resuscitation (DCR) procedures. The remaining years of OIF, 2006–2011, recorded downward trend of DOW soldiers, directly attributed to the improved DCR guideline implementation that focused attention on primarily hemorrhagic injuries (Langan et al., 2014).

The decrease of deaths from this update in DCR practice, though, did not alleviate the large remaining percentage of potentially survivable injuries. As Langan et al. (2014) observed, there was a large number of patients that suffered from head wounds from blast injuries which accounted for 83% of nonsurvivable injuries during the last five-year period of OIF. Thus, this highlighted a need for neurotrauma specialists and additional cranialinjury preventative equipment to be present early (at Role 2 or immediate treatment upon admission in a Role 3) in the continuum of care for injured soldiers (Langan et al., 2014).

A biologic phenomenon that occurred in a significant number of patients who experienced shock trauma was Hyperkalemia. As Stewart et al. (2017) described during a retrospective study on patients admitted to MTFs during combat from 2002 to 2011, nearly 6% of patients were diagnosed with Hyperkalemia, a condition where the human body produces higher levels of potassium from an acute kidney injury (AKI) that can lead to death. Many stabilized trauma patients did not have conclusive test results suggesting they had an onset of Hyperkalemia or were classified as false positives because the trauma suffered contributed to hemolysis, the rupturing of red blood cells. Thus, patient evacuation was not conducted in a timely manner and death was a result although fixed, Role 3 MTFs had the capabilities to treat the patient. Additionally, the materiel and expertise to combat Hyperkalemia does not lend itself to the portable nature of an FRSS or FSRD. If future therapies are developed with a smaller materiel resource footprint, the ability to treat casualties afflicted by Hyperkalemia may exist in Role 2 facilities in the future (Stewart et al., 2017).

Battlefield casualties that occurred in Afghanistan from early 2008 through late 2014 requiring an evacuation from a Role 2 to a Role 3 facility were accompanied by attendants with varying levels of medical experience and training. Of the 3,927 patients transferred, over 40% were not accompanied by a medical attendant even if the need existed (Staudt et al., 2018). This can be attributed to the limited number of medical staff available in austere, forward battlefield environments. Additionally, under qualified medical attendants, such as emergency medical technicians (EMT) were recorded providing en route care and oversight for intubated patients, for which EMTs are not qualified to perform. Furthermore, any delay in lifesaving care in austere environments that was only available from a Role 3 facility, lead to poorer outcomes (Staudt et al., 2018). As advancing medical interventions progress, allowing treatment closer to the point of injury, there will be an implicit need for the appropriate skilled providers in future austere combat environments (Hahn et al., 2019).

Intense, developing conflict during OIF lead to the precipitous deployment of over 32,000 U.S. military personnel to Iraq during the early months of 2007 (Lesho, 2011). Given the large influx of troops and devastating battlefield engagements as a product of shifting military strategy to counterinsurgency operations, the number of trauma casualties skyrocketed. As Lesho (2011) describes, personnel composition now included large numbers of National Guard and civilian contractors that contributed to an older force with a broader range of existing medical issues. Military doctrine pertaining to medical staffing did not address this need, thus Role 2 and 3 facilities were not staffed with the appropriate provider specialties to treat much of the patient population. Prospective research showed that without a complement of mental health and cardiologists present in a Role 2 facility, of the 8,083 patients observed, over 1,500 more patients would need to be evacuated to Role 3 facilities that, in many cases, were several hours away from the patient's location (Lesho, 2011). Immediate healthcare provider attention in order to diagnose, treat, or inspect of ailing patients has, and continues to be, mostly through in-person, collocated interactions. This is due to the necessity for providers to assess the condition of a patient visually, audibly, and physically through their own discernment or by analyzing the outputs of medical instruments. With the advancements in computing and networking capabilities that enhance audio-visual technologies, the synchronous interaction of providers and patients can be conducted while each person is thousands of miles apart from one another.

C. TELEMEDICINE

The literal form of telemedicine in terms of science of practicing disease prevention and health maintenance from a distance, has been practiced in several ways throughout the last thousand years. From sending smoke signals to warn distant tribes of spreading diseases to more recently, radiological scans for an asynchronous diagnosis determination (Waller & Stotler, 2018). Specifically, radiologists can review computerized tomography (CT) and magnetic resonance imaging (MRI) scans taken from any facility by digitally receiving the images or accessing digital archival repositories (Zanaboni & Wootton, 2012).

In-patient provider visits, or where vital diagnostics are needed, can be conducted while the physician is distance located and needs to do nothing more than to speak and have another person such as another physician, nurse, or medical technician to utilize auxiliary equipment on the patient. Blood pressure tests; visually inspecting oral, nasal, and aural cavities; and listening to bodily functions through stethoscopes can be transmitted digitally for assessment. Ambulatory patients needing a routine health-check have the ability to be located nearly anywhere by using a mobile device equipped with audio (microphone and speaker), video (camera and screen), and internet (mobile or home network) capabilities, that allow a physician to communicate with the patient (Waller & Stotler, 2018).

As Waller and Stotler (2018) described, the benefits of telemedicine vary broadly and notably include:

- Cost savings from eliminating the necessity for patients to travel to a provider, or vice versa
- Broadens access of specialty care such as mental health or health education to rurally located patients
- Ease of use to schedule, “arrive to,” and adhere to appointments for a digitally native population
- Immediate access for patients and providers to connect
- Saved work and school days
- No differences in patient outcomes between in-person and telemedicine treatment for certain health conditions
- Technological advances allow for broadening practicing specialty care such as dermatology, psychology, and rehabilitative therapy

D. ROBOTIC ASSISTED MEDICAL CAPABILITIES

Robotics began as an idea mentioned in literature by the writer Isaac Asimov (Parekattil & Moran, 2010). His short story "Runaround" can be traced back to the World War II era and centers around the concept of a robotherapist. Over a decade later, in 1956, this concept inspired two men to create a commercially viable robot. The successful inventor George C. Devol and an engineer named Joseph F. Engelberger embarked on a joint venture with the financial backing of Condec Corporation to design and produce the first robot (Parekattil & Moran, 2010). The company was called "Unimation," which is short for universal automation. Five years later their tireless efforts produced the first robot, called 'Unimate' and led to Engleberger's reputation as the father of robotics (Parekattil & Moran, 2010). Unimate was implemented in a General Motors plant to perform work that was repetitive in nature and had a history as unsafe for a human (Parekattil & Moran, 2010). Hazardous and boring summarizes the early work of robots in industrial applications, but it was a job description they were perfectly suited for.

Robotic interest and development in the following decades grew significantly outside of the United States. Other countries, such as Japan, became leaders in the application of robots in manufacturing and remain that way as of the time of this writing. American Machine and Foundary developed the Versatron in 1967 and sold it to Japanese automobile manufacturers (Parekattil & Moran, 2010). While early robots used hydraulics to operate, the Programmable Universal Machine for Assembly (PUMA), was developed in 1978 by Victor Scheinman and featured electronic motors. This shift to electric motors enabled much smaller designs and therefore many more areas of suitable applications (Parekattil & Moran, 2010). With the corresponding rise in use of these machines, the Robots Institute of America published the first definition of the word robot: "A reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks" (Leal Ghezzi & Campos Corleta, 2016).

The thought of using robots to assist in medical applications and surgery has been alive and well for over three decades now, as the expectations and possible use cases of this now scaled down robotic capability grew. Not only could a robot perform boring and hazardous tasks, but with the small size of electronic motors and precision of servos, medical applications became possible. In 1985, PUMA was used in neurosurgical biopsies (Leal Ghezzi & Campos Corleta, 2016). Follow on pre-programmable robots such as a the surgeon-assistant robot for prostatectomy (SARP), prostate robot (PROBOT), and UROBOT for urological procedures further enabled surgeons' capabilities while minimizing invasiveness (Leal Ghezzi & Campos Corleta, 2016).

The continued advances and refinement throughout the 1980s garnered great interest in the field from the Department of Defense and along with that interest came funding for further development in battlefield casualty care. Additionally, the Bush administration's plan to eventually send a human to Mars, garnered funding from the National Aeronautics and Space Administration (NASA) Ames Research Center for surgery capability from a remote hospital (Parekattil & Moran, 2010). This funding made possible the development of a head-mounted display (HMD) by Michael McGreevey and Stephen Ellis. The HMD was a stereoscopic display unit with 3D vision. Scott Fischer added 3D audio to the HMD and was the first to generate the idea of telepresence (Leal Ghezzi & Campos Corleta, 2016). Telepresence, according to Parekattil and Moran, is the "notion that one person could be projected with the immersive experience of another (real or imaginary)." The HMD, when combined with the data glove developed by Jaron Lanier, permitted a person to interact with a virtual environment. Simultaneous developments at Stanford Research Institute (SRI) by Philip Green and Richard Satava enabled instrument telemanipulation. The HMD, data glove , and SRI telemanipulator formed the basis of the telepresence surgery conceptually, however it proved to be infeasible in practice at that time. Later iterations used monitors in place of the HMD and hand controllers instead of the data glove (Leal Ghezzi & Campos Corleta, 2016).

The early 1990s continued evolution brought forth the concept of a master-slave robot. This entailed a surgeon sitting at a workstation remotely controlling a robot with manipulators (Leal Ghezzi & Campos Corleta, 2016). One of the first master-slave robots approved for use was the Automated Endoscopic System for Optimal Positioning (AESOP), which used a surgeon's voice commands to move an endoscopic camera. Yulin Wang, the founder of Computer Motion Inc., which developed AESOP wanted to go further with the master-slave concept and received funding from the Defense Advanced Research Agency (DARPA) to create a robot that could mimic the arms of a surgeon (Leal Ghezzi & Campos Corleta, 2016). The result of his efforts was the ZEUS robotic surgical system, which was composed of a surgical console on wheels and a robotic arm station.

During this same timeframe, Frederic Moll, Rob Yonge, and John Freund were very intrigued by the telepresence concept mentioned previously. They joined together and formed Intuitive Surgical, which created a similar surgical device. “The device comprised three main components: 1) a master-slave software-driven system that provided control of seven-degree-of-freedom robotic instruments, 2) a three-dimensional immersive vision system, and 3) a sensor-based safety monitoring system to continuously reassess the device’s performance to maximize patient safety” (Parekattil & Moran, 2010). In 2003, Computer Motion merged with Intuitive Surgical and the result was the termination of ZEUS development. The da Vinci surgical system has continued to be developed and refined ever since gaining the Food and Drug Administration (FDA) approval in 2000 (Leal Ghezzi & Campos Corleta, 2016). Some notable upgrades are 100x digital visual magnification and real-time Doppler monitoring, which aid in laparoscopic surgery success (Parekattil & Moran, 2010). According to the Intuitive website, as of May 2019 over 6 million patients have undergone minimally invasive surgical options utilizing the da Vinci system.

Figure 1. The da Vinci surgical system – Patient cart, surgeon console, vision cart. Image from Intuitive at https://www.davincisurgery.com/da-vinci-systems/about-da-vinci-systems##.

E. TELESURGERY

Expanding medical advancements to a "*tele*" capability has immeasurable benefit, not least of which is the ability to provide immediate, specialized surgical capabilities to patients anywhere in the world. Systems such as the *da Vinci* telesurgery robot has successfully conducted millions of surgeries for patients to receive care from specific surgeons, without the need to ever be collocated (Kovács et al., 2013).

Beneficial outcomes of telesurgery utilizing precision-based robotic techniques were observed in several surgical procedures such as lysis of adhesion, colorectal, and adrenalectomy. Overall, patients experienced fewer complications, lower procedural costs, and shorter in-patient lengths of stay over the traditional, in-person surgery (Salman et al., 2013).

Further remote treatment of patients has been exemplified in emergency situations, with operator-controlled and semi-autonomous robotic modalities. Again, not a colloquially considered practice of telemedicine, but ability for healthcare providers to gather lifesaving information on injured patients through audio-visual technology has been seen in disastrous situations such as the attacks on the World Trade Center in 2001 and flood-trapped individuals during the aftermath of Hurricane Katrina in 2005 (Williams et al., 2019).

Future developments to refine telesurgery will further expand the ability to operate in austere, remote environments. These findings will be significant in Some of the most notable include physiologic tremor cancellation to increase accuracy of the procedure and virtually realistic, immersive capabilities that also allow for multiple surgeon collaboration in real-time (Choi et al., 2018). Findings from developments such as these will greatly contribute to the network topology, hardware, and protocol requirements, and needed to operate the Taurus-M in austere, battlefield environments.

Refinements to military medical doctrine has been predicated from the studies and experiences of those who have provided medical care, particularly from the most recent battles in Iraq and Afghanistan. Each role of care has limitations to the type and availability of care when a trauma induced injury occurs, whether it be due to the limits of personnel or the location of specific providers. Telesurgery has expanded the possibility to forward project life-saving assistance and expertise into limited spaces and environments without the need to collocate the provider and patient. The following chapter will explore a current medical robotic capability, the Taurus-M, and its ability to provide a varietal range of medical assistance by a remotely located, qualified physician. Additionally, it will examine a multitude of limiting networking factors and existing capabilities to mitigate those factors when establishing a remote connection to the Taurus-M in austere locations.

III. RESEARCH APPROACH AND TECHNICAL BACKGROUND

A. RESEARCH APPROACH

After researching the history of robotic assisted surgery capabilities and telemedicine applications we have the fundamental baseline of how these technologies have evolved and the ways they are currently being implemented. This insight forms the basis of understanding the potential capabilities and benefits of robotic telesurgery. A key component to enabling our research was the establishment of a Cooperative Research and Development Agreement (CRADA) between the Naval Postgraduate School and SRI International for utilization of the Taurus-M robot and associated simulator. With the COVID-19 restrictions at both NPS and SRI International, we were unable to travel to their location and use the actual Taurus-M robot. However, a simulator version was made available and permitted us to gain valuable insight into the use of Taurus-M. Once we gained access to a high-end gaming computer on campus to run the simulation and Oculus Rift virtual reality (VR) goggles to control it, we were able to record observations of movement and capabilities. Furthermore, by utilizing two machines via a remote desktop protocol (RDP) connection, we were able to manipulate the simulator from across the room and observe the effects from this remote connectivity.

Due to a myriad of in-person, collaborative restrictions because of the COVID-19 pandemic, resulting in the inability to establish a connection directly between SRI International and the Naval Postgraduate School, we decided to collaborate with the Army's Telemedicine and Advanced Technology Research Center (TATRC). This collaboration allowed us to learn from their observations and findings with the actual Taurus-M robot. Additionally, TATRC's remote network connection to SRI International's Taurus-M proves the use case example and will soon begin to provide the data necessary to analyze network constraints prior to deployment in wireless field studies. Prospective research will be designed utilizing remote connectivity to the Taurus robot by emerging non-geostationary satellites, as well as using a MANET device, such as the MPU5. These studies will provide insight into a potentially viable deployment of the Taurus-M robot in austere environments.

B. TAURUS-M ROBOT

The Taurus-M robot developed by SRI International is a scaled down version of the DaVinci surgical robot and as such has a very small footprint, making it compatible with small facilities and workspaces. Despite its modular design, weighing only 15 pounds, it has a seven-hour battery life and can be equipped with multiple instruments, including a potts scissors, large needle driver, and black diamond forceps (*SRI International. (2020). Taurus-M Quickstart Guide V1.0.Pdf*, n.d.). These implements can be configured as the user sees fit for the given application. High-definition video is provided through the use of two Sony EV7520 stereoscopic block cameras capable of 30x optical zoom. Stereoscopic cameras provide the impression of depth and solidity for an accurate representation of the environment (Ponce & Born, 2008). Additional lighting is available through both LED and infrared options (*SRI International. (2020). Taurus-M Quickstart Guide V1.0.Pdf*, n.d.). The display and controls can simply be portable devices such as a laptop with HD screen and VR dual hand controllers. This low-cost setup may be beneficial for getting familiar with the virtual environment and early training evolutions with the Taurus-M simulator. However, in order to get the precision capability essential for laboratory or surgical applications, an immersive HD stereoscopic Operator Control Unit with dual haptic feedback 3D hand controllers is required (*SRI International. (2020). Taurus-M Quickstart Guide V1.0.Pdf*, n.d.).

The ability of the robot endpoint manipulators to provide improved range of motion through a continuous roll of the instrument is made possible by a clutch design using foot pedals. Rotating motion of 360 degrees is achieved by using the foot pedal to decouple from the robot. This allows the human operator to reposition hands and then by depressing the pedal again, couple back to the robot providing near continuous rotation. The compact design of the Taurus is pictured in Figure 2.

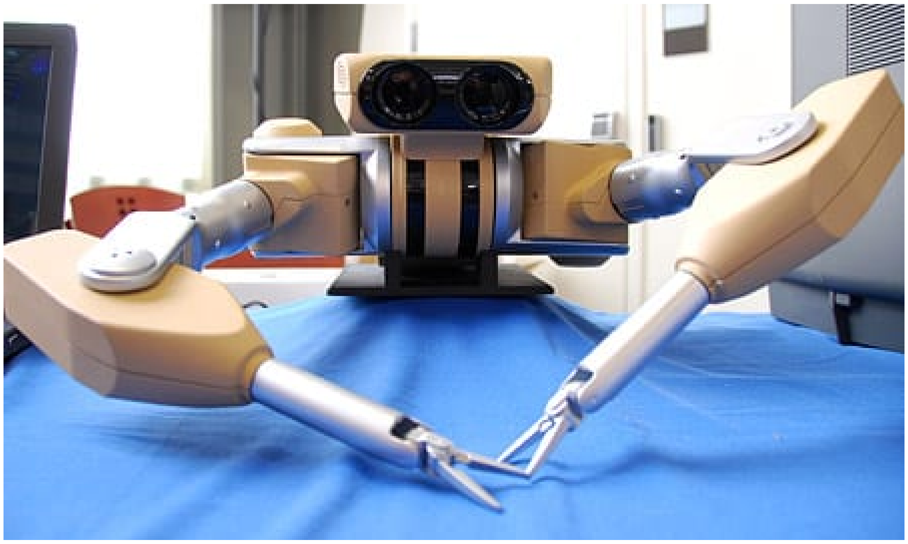

Figure 2. Taurus-M Robot from SRI International. Image from Silicon Valley Robotics at https://svrobo.org/sri-international-behind-new-robotic-technology-for-verb-surgical/.

C. HAPTIC FEEDBACK

Haptic is a Greek word associated with the sense of touch. Specifically, haptics is the discernment and manipulation of things using both the senses of proprioception and touch (Våpenstad et al., 2013). According to the Medical Dictionary (n.d.), proprioception is the awareness provided by the stimuli that are perceived as a result of the touch sensation felt during the movement and position of the body, especially limbs. Proprioception depends on both kinesthetic and cutaneous receptors. Kinesthetic receptors detect muscle and bone movement as well as position. Cutaneous receptors sense pain, heat, texture, vibration, and pressure in the skin (Våpenstad et al., 2013). Given the precise nature of surgery and the fragile nature of human tissue, haptic feedback is considered a vital component when performing robotic assisted surgical procedures. It gives the operator a feeling of the real objects that he is interacting with. This sense of the operating environment allows the manipulator to feel resistance when grasping things and get a sense of how the actions will impact the patient and ultimately achieve the desired result (Våpenstad et al., 2013).

Grasping tissue or skin too forcefully can inadvertently tear or damage it, while not grasping firmly enough can lead to it slipping through, causing unnecessary delays in a time critical scenario. Getting this proprioceptive feeling correct however, in a simulated virtual reality environment has proved very challenging to date (Koehn & Kuchenbecker, 2015). The da Vinci surgical system is the most common Robotic Minimally Invasive Surgery (RMIS) tool available. It is operated from across the room at a surgeon console, however it does not provide a good feeling of what the surgeon is touching with the robotic tools inside the patient. This lack of feeling issue has been minimalized by many surgeons due to the experience gained by repetition of the same procedures. Additionally, some report overcoming the lack of feeling through the enhanced visual cues provided by a crystal clear picture and zoom capabilities (Koehn & Kuchenbecker, 2015).

Despite the ability to overcome the lack of haptic feedback and feeling over time, there are studies indicating that the lack of haptic feedback increases time for robotic assisted surgeries(van der Meijden et al., 2009). The lack of force feedback makes depending on visual cues the sole indicator of correct pressure or actions. This can also contribute to longer training sessions with virtual reality simulators for new surgeons. Psychomotor laparoscopic skills are developed in VR simulators to improve patient safety and ensure the surgeon is proficient with the system and its intricacies prior to stepping into the operating room (Våpenstad et al., 2013). The benefit of near identical VR simulations is a key component to reducing errors and minimizing operating time.

An experiment performed by Koehn and Kuchenbecker aimed to assess the value of feeling while performing surgical type tasks. They “developed a technology that allows surgeons to feel and/or hear the high-frequency vibrations of robotic instruments as they interact with patient tissue and other tools” (Koehn & Kuchenbecker, 2015). The researchers then asked the subjects to rate their level of preference based upon a scale from 0–100. Strongly would not prefer was rated as a 0, while 100 corresponded to strongly would prefer. After analyzing the responses, they found that “subjects strongly agreed that haptic feedback of instrument vibrations made them more aware of the instrument contacts, with a median agreement level of 86 out of 100” (Koehn & Kuchenbecker, 2015, p. 2977)

The first experiment was only done with 20 subjects, so the number of test subjects was expanded in the second experiment to 94. These individuals spanned the spectrum of experience, including subgroups comprised of the following: attending surgeons, fellows, residents, medical students and finally others, who had no medical background (Koehn & Kuchenbecker, 2015). This time the participants spent 4–15 minutes operating the da Vinci surgical system. Multiple conditions were assessed ranging from audio only, to vibrotactile only, to both, as well as neither of the feedback options. The tasks included peg transfer, needle pass, circle cutting and suturing. 100% of the participants responded that the option of haptic feedback was useful (Koehn & Kuchenbecker, 2015). Furthermore, 20 out of 30 attending surgeons found vibrotactile and audio feedback useful, nine found haptics only useful, while only one surgeon said that audio alone was useful. Among medical students, the usefulness of haptic feedback is more pronounced. All respondents found haptic feedback useful and 14% of those preferred haptics alone instead of both audio and haptic feedback (Koehn & Kuchenbecker, 2015).

D. STEREOPSIS

Another key component to enabling remote robotic assisted surgery is the ability to see the environment as close to reality as possible (Ponce & Born, 2008). The Taurus robot has stereoscopic cameras to satisfy this requirement, which provides the user with a true picture by giving depth and dimension to objects in its field of view (*SRI International. (2020). Taurus-M Quickstart Guide V1.0.Pdf*, n.d.). This depth perception and three-dimensional aspect is naturally provided by our eyes through the binocular disparity of the images since they are offset from each other. This is known as stereopsis or stereoscopic depth perception (Ponce & Born, 2008). The brain uses both eyes working together in order to produce a 3D image. This image gives depth perception at a greater level than monocular clues alone. The edges of objects become clear and do not blur into the background with an undiscernible endpoint. This limit at close range is about the width of a fine human hair (Ponce and Born, 2008). Traditional cameras with only one lens would produce a flattened image, which is unsuitable for the clarity necessary to perform surgical manipulation.

E. NETWORK REQUIREMENTS (LATENCY)

Latency is a measure of the delay between the start of a transfer and the initial request for the data. Latency is a component of any internet connection; however it is particularly evident in satellite connections and also remote cellular 4G/LTE environments. With satellites it is primarily due to the extreme distances between their traditional geosynchronous orbit and the earth's surface. Satellite data transfer is limited by the speed of light and ranges from 500–600ms (Graydon & Parks, 2020). In cellular networks, latency depends on both the distance and the strength of signal to a particular tower. Since latency is the lag between requesting data and receiving it, there is a need in video streaming or conferencing applications to minimize it.

Telemedicine applications utilize video conferencing and remote surgical applications need an even lower latency value to provide real time haptic feedback as well as stereoscopic video. Imagine trying to do even a fairly simple task like threading a needle if your eyes and brain took half a second to render an image. Now apply this same visual and sensory delay to a remotely operated robotic assisted surgery (RAS) and the consequences could exacerbate an already precarious situation. According to an interview with Tom Low, director of the robotics laboratory at SRI International, haptic performance and stability with Taurus is very sensitive to latency. "Latency manifests itself in haptics as a perceived increase in viscous drag on the controllers since the haptic forces are derived from the difference between the position of the controller and achieved positions of the end-effector. To compensate, we have introduced a feed-forward term in the haptic servo to reduce the drag feel, but this can be done only up to a point, where stability is critically impacted." Mr. Low said a formal experiment should be performed to find the exact latency limit for low frequency haptic usefulness, however his best educated guess is less than 20 milliseconds (ms).

Vibro-tactile feedback in Taurus is provided by a separate high frequency haptic channel. According to Mr. Low, it is based on 3-axis accelerometer devices in the robot near the graspers. These are sampled and return a resolved vector for each arm, which is scaled and used to drive the haptic controllers. The drive assumes that the acceleration should linearly correspond to a controller force. In order to prevent high frequency signals from feeding back into the commanded position it is sent through a low pass filter, which means that the channel of data is not destabilizing and can be used with higher latency values. Tom stated that this high frequency haptic channel operates at the communications channel latency, while the video has a slightly higher latency. This leads to feeling contact slightly before seeing the confirmation of it. There is consideration to delay the high frequency haptics to correspond with the video in order to improve the user interface experience.

F. NETWORK CONSTRAINTS IN THEATER

The idea of satellite communication technology dates back to 1945 when a science fiction writer named Arthur C. Clarke conceptualized the idea of geostationary orbit satellites for global communication (Graydon & Parks, 2020). By synchronizing the orbit with the rotation of the earth, he theorized that the satellite would never be out of range. This idea came to fruition in the early 1960s with the launch of Echo 1 and Telstar 1. Telstar 1 was the first to transmit video broadcasts across the Atlantic, however due to its elliptical orbit it was only able to do so for about a half hour of its roughly 2.5 hour orbit (Graydon & Parks, 2020). Nonetheless, this instantaneous communication across the Atlantic Ocean was a scientific breakthrough. The space race of the 1960s furthered the design, development, and launch of satellite communication platforms and in 1973 the Defense Advanced Research Projects Agency (DARPA) connected the University of Hawaii and University College London to its own Advanced Research Projects Agency Network (ARPANET). The Atlantic Packet Satellite Network (SATNET) was the first international network to transmit data between U.S., UK and Norwegian research centers. This could be used as an independent standalone network, but also be linked to traditional terrestrial radio and telephone data networks (Graydon & Parks, 2020). Information sharing across the world with near real time data transfer was now a reality and the U.S. military was very interested in the strategic advantage this new technology offered in command and control (C2) applications through increased situational awareness. Secure government and military satellite communications was here to stay.

In the early 2000s during the second Iraq war, the U.S. military's requirement for bandwidth began to exceed the available capacity inherent in DOD satellites (Stanniland & Curtin, 2013). This opened the once forbidden door to the contracted use of commercial satellites and the U.S. military hasn't looked back since. In 2004, commercial providers were responsible for over 80% of DOD satellite capability and utilization has continued to increase. In 2007, over 95% of CENTCOM's Satcom capability was from commercial systems (Stanniland & Curtin, 2013).

The need for information and communication options in austere environments has continued to expand due to new systems like unmanned aerial vehicles and smart weapons being employed throughout the world as the global War on Terror continues into its third decade. This has pushed traditional satellite capabilities to the limit at an astounding price tag (Stanniland & Curtin, 2013). Due to the saturation of existing satellite communications, this paper will examine some newer technologies that are either available now and underutilized or will be coming online in the next couple of years to satisfy the network bandwidth and latency requirements of telemedicine technologies in austere operating environments.

G. POTENTIAL NETWORK SOLUTIONS

O3B mPOWER is a revolutionary advancement expanding the SES O3B Medium Earth Orbit (MEO) Satellite Constellation to provide high bandwidth throughput capability to nearly every area the DOD operates in. This service can bridge the gap between the overutilized military satcom capability and the infrastructure dependent traditional Internet Service. Due to its expansive coverage between 50°N and 50°S latitude, this service is capable of reaching 96% of the global population, from Kazakhstan to South Africa (*O3b MPower Press Factsheet*, 2020) .This coverage encompasses a vast majority of the military operating areas in the current conflicts as of this writing. With individual location bandwidth speeds of 10Mbps-10Gbps and the ability to connect thousands of sites per region, this solution could feasibly link every Role 2 facility with multiple Role 4 facilities and enable the full spectrum of telemedicine capabilities. Providers and medical capabilities that simply aren't available in austere forward operating base locations around the world can be accessible through videoconference and other telemedicine solutions made possible by dependable high throughput connectivity. Maintaining confidentiality and security of information is made possible through the ability to incorporate government-operated gateways and independent subnetworks (*O3b MPower Press Factsheet*, 2020). This gives the units control over the network to implement load balancing rules ensuring Taurus and other telemedicine applications to operate without interruption, while meeting or exceeding the speed and latency restrictions required for haptic feedback.

SES and O3B mPOWER is a proven technology that is readily available now and has been in use for over a decade in telemedicine applications. SATMED, which was developed by the Luxembourg Government partners with SES for connectivity. It has been successfully deployed across Africa and Asia in ten remote locations since the Ebola outbreak in 2014 and continues to provide services during the COVID-19 pandemic ("Luxembourg Government and SES Launch Second Phase of Satellite-Enabled SATMED Telemedicine Project," n.d.).

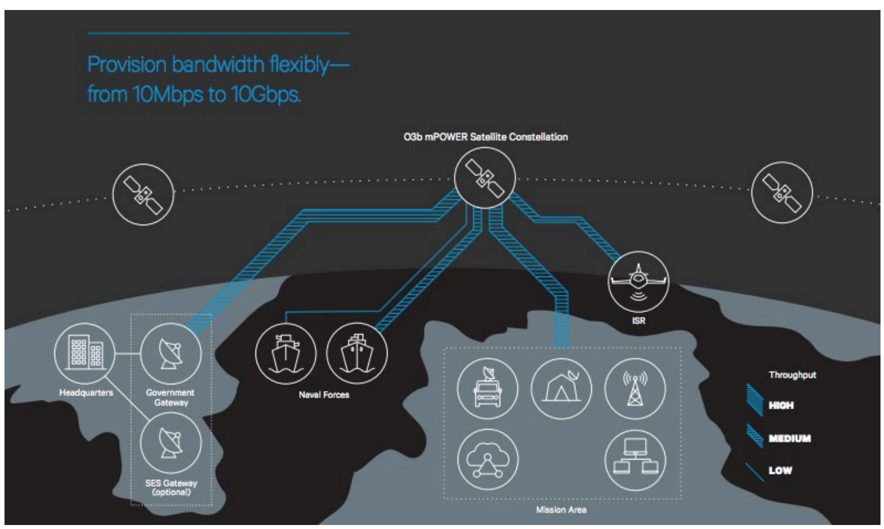

Figure 3. O3B mPOWER coverage area and example applications. Image from O3b mPower at https://o3bmpower.ses.com/industries/government.

An extremely promising technology that will be commercially available in the next year or two is a satellite constellation project by SpaceX known as Starlink. While O3B mPOWER operated in medium earth orbit, Starlink operates in low earth orbit between 500 - 1200km and therefore has significantly less distance to travel, which leads to minimal latency and could even beat existing fiber networks over long distances (Duan & Dinavahi, 2021) Current latency is advertised as 20–40 ms, but is expected to decrease below 20ms as more satellites are launched in the coming years. Future research and experimentation will need to be done for specific latency measurements once Starlink is fully operational, however, as of May 2020 the U.S. Army has signed an agreement to evaluate the network over the next few years (*SpaceX Signs Testing Agreement with U.S. Army for Use of Starlink Network | TechCrunch*, n.d.) There are 12,000 satellites planned, referred to as a megaconstellation, which will provide broadband service across the globe. 4,400 of these will use Ku-band downlinks and Ka-band uplinks, while the second-generation satellites will use V-band. They are designed for a five year lifespan and will then deorbit to burn up in the atmosphere in order to prevent becoming space debris ("SpaceX Seeks FCC Permission for Operating All First-Gen Starlink in Lower Orbit," 2020).

Since SpaceX is already working with the U.S. Army for Starlink evaluation, it is reasonable to assume the Defense Health Agency could enter into a similar agreement for telemedicine application evaluation. The U.S. Army's evaluation ability comes in the form of a CRADA, which is the same type of agreement that the Naval Postgraduate School has with SRI International permitting us to use the Taurus robot and its associated simulator. These agreements are fairly common and allow the military to evaluate private sector technologies before actually purchasing them. Joseph Welch, the deputy program executive officer for command, control, communications tactical (C3T), confirmed the oversaturation of current satellite abilities previously discussed. "One of the problems is that satellites are oversubscribed, provide limited throughput and have high latency" (*U.S. Army Signs Deal with SpaceX to Assess Starlink Broadband*, 2020). He refers to available bandwidth at the tactical level as a soda straw, despite new technologies and weapons requiring a garden hose or fire hose amount of throughput. Despite the enormous jump in speeds promised by Starlink, a couple key concerns arise for remote tactical use. Starlink satellites still need to be tracked by flat panel antennas, so the cost and durability of these is a major concern moving forward. Data security is the primary issue since the system uses ground stations located around the world to transmit data instead of the satellites being optically linked to each other ("U.S. Army Signs Deal with SpaceX to Assess Starlink Broadband," 2020). These concerns are the primary focus of the Army's CRADA enabled evaluation, however the security of data provided by Starlink is more than adequate for telemedicine applications and is therefore an extremely promising enabler for the Defense Health Agency to consider.

The Taurus-M is the most recent progeny of proven robots capable of conducting telesurgery. Its compact design, agile range of motion, and advanced technological features make it a viable solution to bridging the gap that exists when delivering advanced medical care from a remote location. Given the necessity to maintain a high level of acuity, precision, and stabilized movement during in-person surgery, it is only reasonable that these requirements are met or exceeded when utilizing surgical robotics. The low speed of transmission and miniscule bandwidth allocation through many satcom networking options lack the ability to meet the requirements necessary to operate the Taurus-M without the concern for patient safety due to excessive latency and degraded visual quality. Technologies, though, such as O3B mPower and Starlink have the potential to provide the necessary bandwidth with optimal throughput speeds that will allow the operators to seamlessly maximize the potential operational capabilities of the Taurus-M. The following chapter will explore the observations made while utilizing the Taurus-M robot and its companion simulator software. Through these observations and adapting it to the myriad of telemedicine requirements, we are able to delve further into the realm of possible solutions when manipulating surgical robots in austere environments.

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IV. OBSERVATIONS AND FINDINGS

The Taurus-M simulator is the base to which every operator must become familiar with before using the actual Taurus-M robot. Getting familiar with the basic movements, functionalities, and limitations allows operators to make errors without any repercussions that may come from exceeding the Taurus-M robot's limitations in movement. This shared simulator environment is the fundamental baseline, which can be built upon for further CRADA enabled collaborative research and testing between the Naval Postgraduate School and SRI International, as well as TATRC's TRON project involving several other academic institutions.

Figure 4 is of the Taurus-M robot simulation from an operator's point of view from within the Oculus Rift VR headset. Multiple functionalities reside within the "console" view for the operator to alter various states of the Taurus-M:

- Stow – retracts the arms and instruments and set the Taurus-M into an inactive state
- Approach – deploys the Taurus-M robot to the operating platform
- Safe – positions the Taurus-M in a manner so that the camera's field of vision is directed at the working environment and the arms are extended with instruments within reach of the objects the operator will be manipulating

Indicators are available for the operator to identify the connectivity or operational status of certain components of the Taurus-M or of their own remote controls. This allows the operator to quickly identify and troubleshoot disconnects in major components such as the left and right control arms, camera tilt motor, touch controllers, foot pedals, and video connectivity. Additionally, each arm can separately change between surgical instruments such as Potts scissors, needle driver, and the da Vinci black diamond forceps. As seen in Figure 5, a third person view of the Taurus-M is located to the right peripheral operator view for a quick cognizance reference of the Taurus-M's arm position and its physical relation to the operating subject. This console view within the simulator is identical to the console view when operating the actual Taurus-M.

Figure 4. Operator’s console view within the Taurus-M simulator

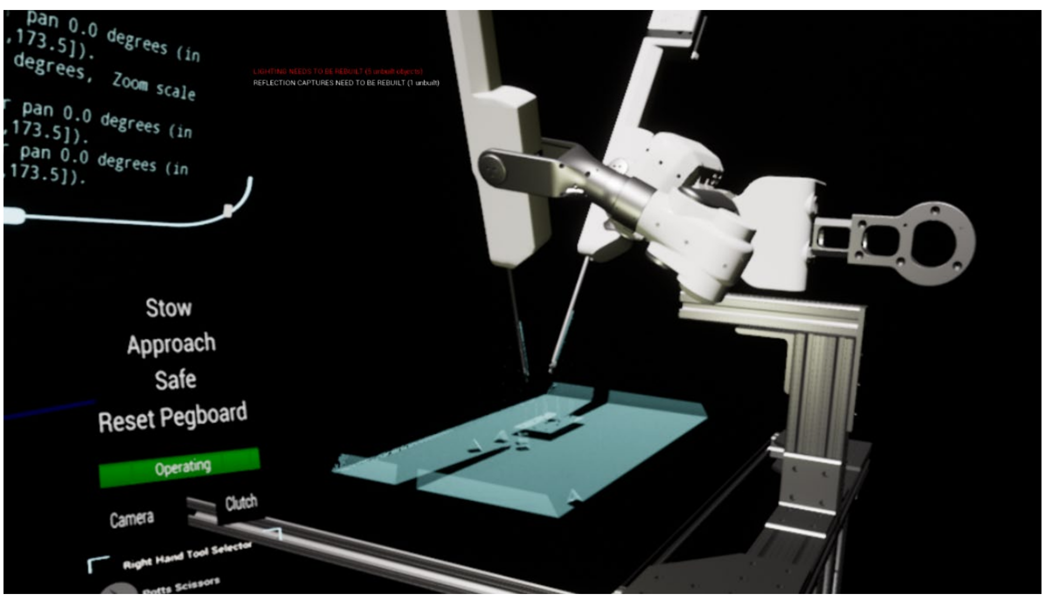

Figure 5. Peripheral third person view of the Taurus-M simulator

Through utilizing a standard Oculus Rift VR headset with the simulator software, our interaction with the Taurus-M was done within an NPS simulation lab.. Since the Taurus-M is mounted in a static position over an operating area, there is not a need for the operator to move away from a standing or seated position. The resolution of the view of the pegboard was adequate to identify the position of the Taurus-M's arms, hands, instruments, and any pegboard peripherals. Utilizing the VR controllers, we found that the movement of the robotic arms correctly replicated the movement that was trying to be achieved. Such movements included wrist manipulation, grasping, clamping of tools, visual movement within the operating console, and visual change of the Taurus-M's camera on the operating area. When reaching the physical rotation limits of the robot, tactile vibration feedback was provided along with a notification of what caused it. Since the limitations of the robot exceeded that of our own natural wrist or arm movement, disengaging the foot pedal clutch allowed for the user to reposition their wrist or arm into a comfortable position and continue moving the simulated arm or wrist by reengaging the foot pedal clutch.

A digital zoom feature allowed us to get a closer view of the pegboard and instrumentation manipulation. The focal clarity, though, was suboptimal with no magnification and exaggerated when zooming in to focus on smaller details of the instruments and pegboard. Manipulating the square and triangular pieces to align onto posts on the board was very difficult without magnification. Again, when the focal point of the robot was magnified to see the pieces in finer detail, the resolution was very poor (Figure 6). But, the movement of the robotic arms, in a magnified view, was far less. Such that, our arm and hand movements needed to be proportionately greater than that of the robot's. It was apparent that this proportionality adjustment in a magnified view allowed us to appear much more stable in finer detailed manipulation with less implied movement error. Overall, the visual appearance within the VR headset when manipulating the Taurus-M simulation did not provide a consistent, clear picture. This was problematic when it came to conducting tasks such as grasping and threading multi-dimensional blocks onto a peg. Tasks that are trivial and physically simple without the aid of a robot.

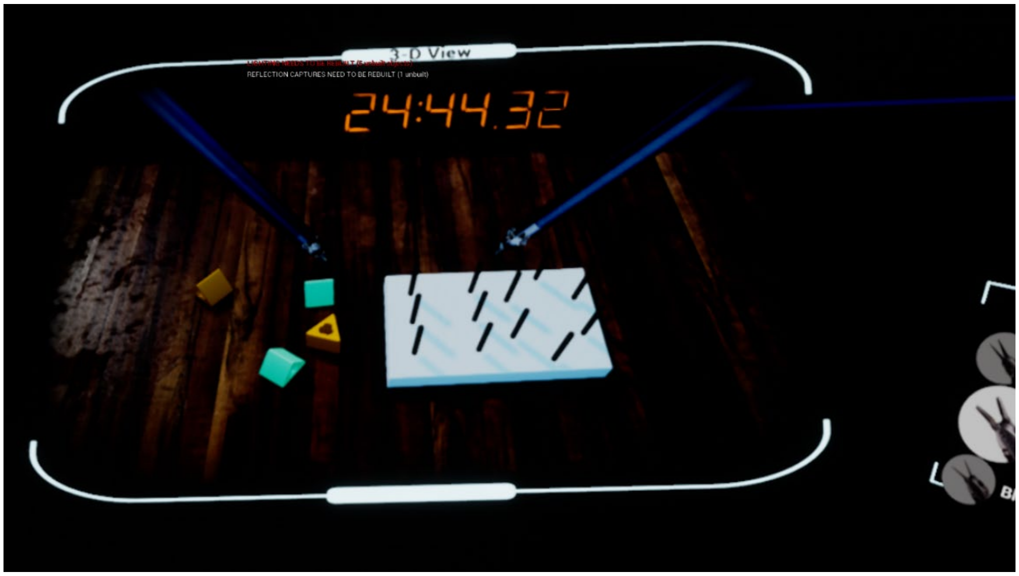

Figure 6. Magnified view of operating field and pegboard

To create a physical separation of the simulator and the operator controlling it, a remote connection was established to a separate lab computer. This allowed the operator to use the Oculus Rift VR headset and its controllers to manipulate the Taurus-M simulator, which was simultaneously running on a different computer. No distinguishable difference in movement response from operator to simulator was recorded and latency of transmissions between both computers was indiscernible and did not impact the simulator movement. Visual clarity continued to be suboptimal, which continued to hinder precise movement and manipulation of the Taurus-M simulator.

TATRC's observations and experiences during Taurus-M simulation manipulation from Ft. Meade, Maryland to the SRI International campus were accomplished through a remote access connection. The physical distance between the sites is approximately 2,793 miles. Although connectivity was successful, data packet loss was experienced during operation. This packet loss resulted in a degraded visual display of the Taurus-M's simulated movement. Furthermore, the pixilation that was observed left an inaccurately rendered view of the visual output during both static positions and the movement of the Taurus-M. Recorded movement time from the simulator operator located within TATRC saw no problematic latency, thus suggesting that user movement from the VR headset to the operating machine was performing within the acceptable range of less than 150 ms, while still considering the Taurus-M's native latency of 50 ms. This performance was to be expected since the experience while operating the Taurus-M simulation software on the locally connected computer. Additionally, TATRC operators used an Oculus Rift-S VR headset which utilizes a higher pixel resolution screen than the Oculus Rift, thus the visual clarity for the operator is significantly enhanced. The difference in resolution capabilities is the accepted reasoning for our degraded view while using the simulator. It is highly recommended that any future use of the simulator is done with the Oculus Rift-S VR setup. The visual acuity upgrades combined with inside-out tracking is necessary to take full advantage of the simulator's capabilities.

Operators at TATRC noted no noticeable difference in movement response time, fluidity of movement, anticipated movement behavior (roll, pitch, and yaw of instrumented arms) or visual representation between that of the simulator and actual surgical robot. The operator's picture through the console viewfinder, though, is replaced with a high-definition video feed from the Taurus-M's point of view camera (Figure 7). As seen in Figures 8 and 9, a live third person view and a dashboard to monitor patient vital signs is available.

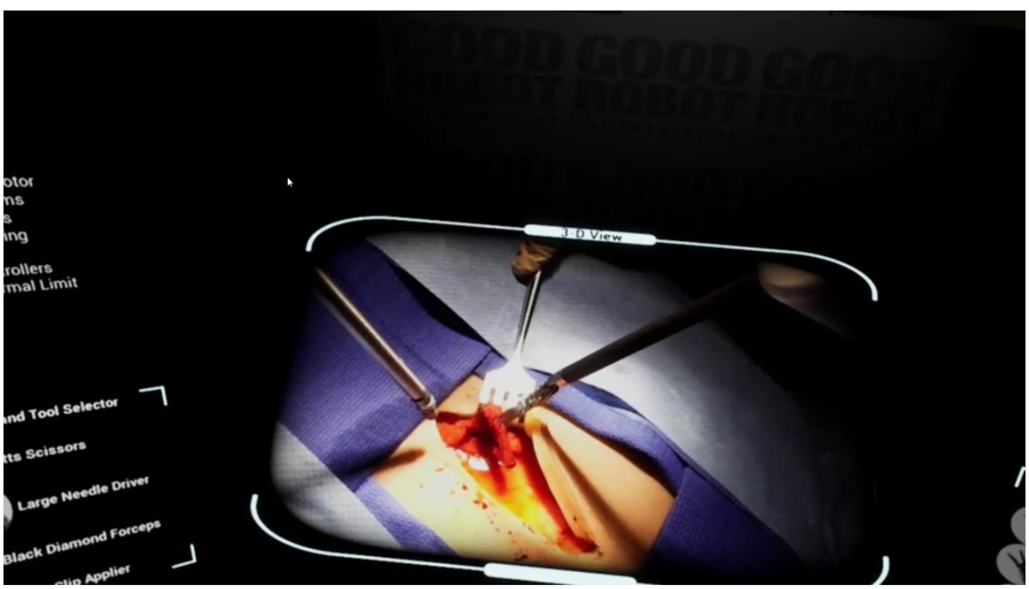

Figure 7. High-definition video feed from the point of view camera

Figure 8. Third person live view of Taurus-M robot

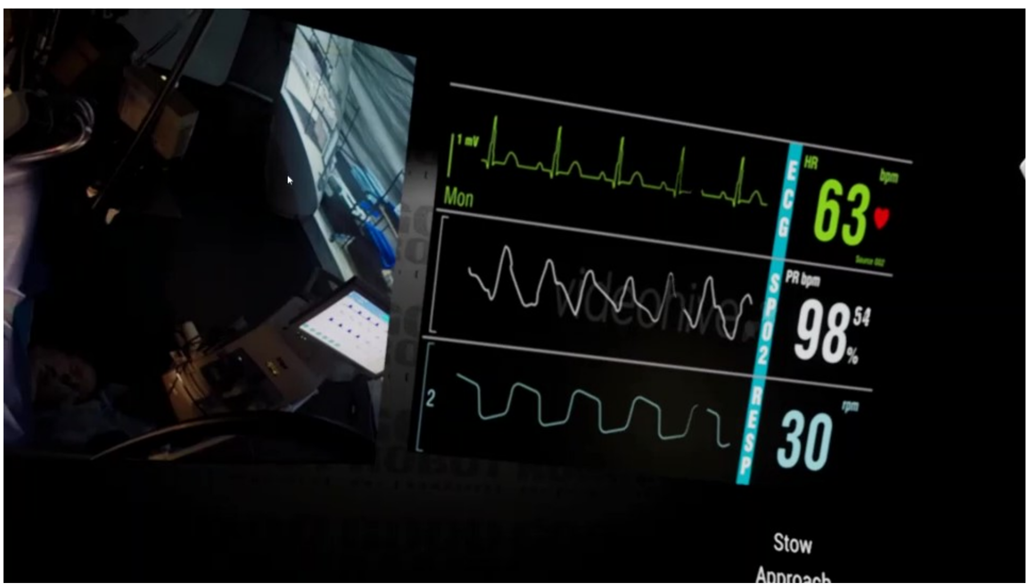

Figure 9. Patient vital signs monitor

During procedures that required precision movement of the robot, the ability to magnify the operator's view coupled with the physical movement of the operator being proportionately less, allowed for consistently safe movements. Thus, lessening the concern of error from the naturally larger movements of the operator such as involuntary hand stutter.

As this emerging technology continues to evolve there will likely be other issues that arise that will present when incrementally moving the Taurus-M further away from the point of operator control. Though the cross-country connection between TATRC and SRI was successful by using the current land-based networking infrastructure, the information that it received was not transmitted correctly given the protocol used. The distances that span between Role 2 and 3 facilities will likely not be as far when considering the use of the Taurus-M in an austere environment, but it will face the need to transmit information wirelessly. Limited wireless bandwidth and discovering the most efficient routing protocol(s) will be new testing determinants towards the effort in ensuring a stable connection for the safe use of the Taurus-M.

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V. CONCLUSION AND FUTURE CONSIDERATIONS

Robotic telemedicine capabilities in austere environments are well on their way to becoming a reality in the near term. With the compact footprint and portability offered by a unit such as the Taurus-M, it is reasonable to envision a robotic surgical assistant device at all DOD Role 2 medical facilities. Additionally, recent advancements in satellite technology with drastically lower latency rates due to their lower earth orbit patterns, make this remote capability for austere environments in the realm of the possible. The benefits of this technology as a force multiplier cannot be overstated. We were able to gain familiarity with the simulator and demonstrate remote operation of it via RDP connection. In addition to this research, there are several other institutions involved in evaluating the limitations and capabilities of robotic telemedicine.

However, since it is still an emerging technology there is still an abundance of research to be conducted. Due to the limitations of the COVID-19 environment, we were unable to complete much of the planned quantitative analysis regarding network degradation impacts with the robot. Future research should be conducted in collaboration with TATRC at Ft. Detrick, MD and its TeleRobotic Operator Network (TRON) project. This paper is directly aligned with TRON's mission: "to establish a semi-autonomous robotic framework that will enable safe and effective telesurgery in forward care environments by accommodating for the deleterious effects of signal latency and disruption" ("TATRC.ORG – Meet TRON: A TeleRobotic Operator Network | MISL," n.d.). Further collaborative effort will enable network connection between institutions and serve as another proof of concept for remote surgical operation. By collecting data on the latency and throughput of this terrestrial connection as it is throttled down, future researchers can determine the lower limits of bandwidth required and the upper limits of latency at which remote robotic usefulness is lost. Additionally, by exploring robust header compression (ROHC) to optimize real-time transport protocol (RTP) and user datagram protocol (UDP) header ratios to reduce the errors in real-time video streaming will provide a better visual to physicians when aiding or performing remote surgeries (Farouq et al., 2020). This data will be critical in determining what network requirements need to be contracted to support its use in forward care austere environments. Furthermore, wireless connectivity options can be explored, including MANET solutions, if network access is anticipated to have to be relayed from another forward location.

In addition to the quantitative network analysis to ensure requirements are fully understood, further research should be conducted into the anticipated barriers of remote surgical technology adoption. There are several entities who will be stakeholders when a form of robotic surgery becomes a program of record. Identifying those individuals and entities early will help to ensure success. A proven model to consider for addressing this is the Technology Acceptance Model developed by Fred Davis in 1989. The external variables of system characteristics, user training, user participation in design, and the nature of the implementation process directly affect both the perceived usefulness and perceived ease of use, which ultimately impacts actual system use (Davis, 1989). By identifying the attributes of these first three external variables early in the design process, future researchers will have a better understanding of the likelihood of actual system use and can then suggest ways to address system shortcomings or user apprehension through training and/or the nature of the implementation process as remote robotic assisted surgery becomes reality.

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