# STINGRAY: HIGH-SPEED TELEOPERATION OF UGVS IN URBAN TERRAIN USING DRIVER-ASSIST BEHAVIORS AND IMMERSIVE TELEPRESENCE

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## ABSTRACT

In order to extend the usefulness of small unmanned ground vehicles (UGVs) to a wider range of missions, we are developing techniques to enable high-speed teleoperated control. Our goal is to quadruple the speed of teleoperated UGVs compared to currently deployed models. The key limitation is not mechanical, but in the capability of the operator to maintain situational awareness and control at higher speeds. To address these issues, we are developing technologies for immersive teleoperation and driver-assist behaviors. Our immersive teleoperation system uses a head-mounted display and head-aimed cameras to provide the operator with the illusion of being in the vehicle itself. Driver-assist behaviors will reduce the cognitive load on the operator by automatically avoiding obstacles while maintaining a specified heading or following a building wall or street. We have demonstrated immersive teleoperation on the iRobot Warrior UGV and a high-speed surrogate UGV. In the near future, we will integrate driver-assist behaviors and improved immersive teleoperation on a high-speed Warrior and test this system in realistic MOUT environments.

## 1. INTRODUCTION

Small UGVs such as the iRobot PackBot have revolutionized the way in which soldiers fight wars. A typical UGV transmits video from an onboard camera back to the operator control unit (OCU) that displays the video on a computer screen. In a manner similar to playing a first-person shooter video game, the operator teleoperates the UGV using a joystick, gamepad, or other input device to control vehicle motion. While this teleoperation method works well at slow speeds in simple environments, viewing the world through a fixed camera limits the operator's situational awareness about the environment. Even joystick-controlled cameras that pan and tilt can be distracting to operate while driving the vehicle. This is one of the reasons why small UGVs have been limited to traveling at slow speeds and missions where these speeds are tolerable.

Faster small UGVs would be useful in a wide range of military operations. When an infantry squad storms a building held by insurgents, speed is essential to maintain the advantage of surprise. When a dismounted infantry unit patrols a city on foot, the soldiers need a UGV that can keep up. However, driving at high speeds through complex urban environments is difficult for any vehicle, and small UGVs face additional challenges. Small UGVs need to steer around obstacles that a larger vehicle could drive over. A bump that would be absorbed by a large vehicle's suspension can send a small, fast-moving UGV flying into the air.

Figure 1: iRobot Warrior UGV with Chatten Head-Aimed Remote Viewer (HARV)

For the Stingray Project, funded by the US Army Tank-Automotive Research, Development and Engineering Center (TARDEC), iRobot Corporation and Chatten Associates are developing technologies that will enable teleoperation of small UGVs at high speeds through urban terrain. Our approach combines immersive telepresence, which gives the operator the impression of being in the vehicle, along with semi-autonomous driver-assist behaviors, which command the vehicle to safely maneuver according to the driver's intent. These behaviors are similar to modern fighter aircraft, which are designed to be dynamically unstable and can only be controlled through software that interprets the pilot's control inputs.

In Phase I of the Stingray Project, we mounted a Chatten Head-Aimed Remote Viewer (HARV) on an

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iRobot Warrior UGV prototype (Figure 1) and a surrogate small UGV based on a high-speed, gas-powered, radio-controlled car platform (Figure 3). The operator wears a head-mounted display and a head tracker (Figure 2). The display shows the video from the HARV's camera, which is mounted on a pan/tilt/roll gimbal. The HARV tracks the operator's head position and turns the camera to face in the same direction.

For Phase II of Stingray, we will increase the Warrior UGV's top speed by developing a high-speed, wheeled version of the Warrior (Figure 5). To assist the driver in controlling this speed, we will reuse the street-following and perimeter-following behaviors developed for the TARDEC-funded Wayfarer Project. These behaviors use LIDAR to determine the orientation of features such as street boundaries, building walls, and tree lines. During Wayfarer, we demonstrated that the performance of this system is robust to irregularities in both urban and rural terrain (Yamauchi, 2006).

With these capabilities, operators will be able to drive the Stingray UGV at much higher speeds than current small UGVs. Stingray will be able to keep up with soldiers in high speed operations and extend the tactical value of small UGVs to a wide range of infantry missions.

## 2. CHATTEN HEAD-AIMED REMOTE VIEWER

Chatten Associates conducted pioneering research in high-speed teleoperation of remote ground vehicles under two DARPA contracts in the late 1960s and early 1970s. Our head-aimed vision technology was then used by the US Army in the Cobra AH-1 and Apache AH-64 helicopters. The US Navy's SPAWAR group successfully used this technology to remotely operate dune buggies and HMMWVs in the late 1980s and early 1990s.

Testing of remotely operated ground vehicles on DARPA and Army Research Lab (ARL) contracts has shown that head-aimed vision improves teleoperation mission performance between 200% and 400%, depending on the task. In general, as the complexity of the task increases, the relative advantage provided by head-aimed vision is much greater.

Under contract to ARDEC, Chatten Associates has developed the ruggedized HARV suitable for operating a small robotic ground vehicle. Previous experiments (Massey, 2004) have shown that only head-aimed vision can provide sufficient awareness for teleoperation at these speeds.

Figure 2: Operator driving vehicle using Chatten HARV

Figure 2 shows a remote operator driving a vehicle using the HARV. The operator wears a head-mounted display that shows the current view through the HARV cameras and a head tracker that monitors the operator's head position. As the operator turns his head, the HARV gimbal automatically turns the cameras to face the corresponding direction. This provides a far more immersive experience than aiming the camera with a joystick (even with the same head-mounted display).

## 3. WARRIOR/HARV INTEGRATION

We successfully integrated the HARV with a Warrior UGV prototype. The HARV is powered by a DC-to-DC converter that provides regulated 24V from the Warrior's unregulated 48V system voltage. The operator wears the HARV and drives the Warrior via joystick control using the prototype's R/C control interface. Analog video is transmitted back to the operator using a 2.4 GHz transmitter. Digital commands to update the camera position based on the operator's head position are transmitted on a separate channel at 900 MHz.

Using this setup, we were able to successfully teleoperate the Warrior using the HARV through both open and wooded terrain and over grass, asphalt, snow, and concrete curbs. We were able to drive the Warrior at the prototype's current maximum speed while making turns and avoiding obstacles.

Experienced Warrior operators reported substantial increases in situational awareness. The operators were able to control the robot non-line-of-sight at full speed through a grove of trees, without any difficulty. Based on post-run operator evaluations, head-aiming increased situational awareness by nearly an order of magnitude over the fixed camera solution that had been used previously. The operators felt very comfortable with full speed operations in areas where they would have been reluctant to otherwise venture.

## 4. HIGH-SPEED SURROGATE UGV

In order to gather experimental data on the high-speed teleoperation issues during Phase I, we used a surrogate high speed UGV (Figure 3). The surrogate UGV consists of a 1/5 scale radio-controlled, gas-powered Ford GT with a top speed of 50 mph (80 kph). This car, a Hobbypro Model H5, is 36 inches (92 cm) long and 21 inches (53 cm) wide, and weighs 9 kg. It is powered by a 23cc engine that runs on a mixture of gasoline and two-stroke oil (25:1 ratio), and is equipped with four-wheel disc brakes. The car is controlled by a two-channel FM transmitter that provides proportional control of steering and throttle/braking.

Figure 3: Surrogate UGV driving through slalom course

We removed the outer shell of the car and integrated the HARV and a roll cage with the surrogate UGV. In this configuration, the surrogate was also able to reach an estimated top speed of 30 mph (48 kph). To the best of our knowledge, this surrogate is the fastest man-portable UGV to ever be tested.

The vehicle had three radios: a 75 MHz pulse-width modulated radio for vehicle steering, throttle, and braking; a 1.7 GHz analog radio for NTSC video; and a 2.4 GHz digital radio for gimbal control. The 75 MHz radio had a maximum range of about 250 feet (76 m).

We tested the surrogate UGV on a slalom course (Figure 4) shows the layout of the course, using 16 traffic cones on a large, flat asphalt surface, measuring approximately 40 x 80 feet (12 x 24 m). The yellow circles in this figure represent cones, and the arrows indicate the car's direction of travel when passing through the gate between the adjacent cones.

In all of our experiments, the operators wore the HARV head-mounted display and controlled the vehicle using the hand-held R/C proportional controller (with a small wheel controlling steering and a trigger controlling throttle and brakes). In the first set of experiments, the gimbal was locked down so that its orientation was fixed with respect to the vehicle. In the second set of experiments, the HARV gimbal was enabled, and the cameras orientation was controlled by the operator's head motions.

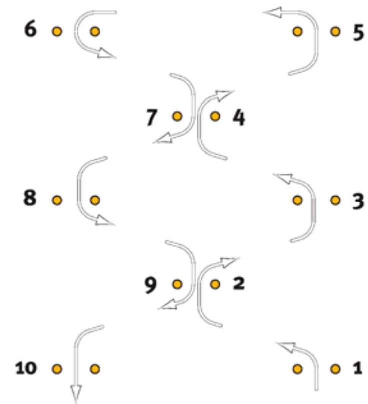


Figure 4: High-speed slalom course
(yellow circles indicate cones; arrows indicate vehicle direction through gates)

| | Time | Cones Hit | Gates Missed |
|---|---|---|---|
| **Operator 1** | 28.7 | 1 | 1 |
| | 28.3 | 0 | 0 |
| | 26.2 | 0 | 0 |
| **Operator 2** | 39.7 | 0 | 0 |
| | 34.1 | 0 | 0 |
| | 36.1 | 2 | 0 |

Table 1: Results from high-speed slalom experiments using fixed camera

| | Time | Cones Hit | Gates Missed |
|---|---|---|---|
| **Operator 1** | 29.6 | 0 | 1 |
| | 30.5 | 2 | 0 |
| | 28.5 | 0 | 0 |
| **Operator 2** | 34.2 | 0 | 0 |
| | 33.8 | 1 | 1 |
| | 49.4* | 0 | 2 |

Table 2: Results from high-speed slalom experiments using head-aimed camera
(* = battery low, resulting in loss of control authority)

Our experiments showed that both operators were able to successfully navigate the slalom course at high speed using the HARV in either fixed or head-aimed mode. Table 1 and Table 2 show the results from these experiments. Operator 1 was more experienced with high-speed driving of full-sized automobiles and did slightly better with the fixed camera. Operator 2 did not have the same background in high-speed driving at full-scale, and he drove more slowly in both conditions than Operator 1. Operator 2 appeared to benefit somewhat from head-aiming, as it gave him more confidence in turning into the next set of cones.

In a course that more closely resembles an urban environment, with limited line-of-sight and the need to look around corners, other experiments have shown that head-aiming results in a substantial improvement in operator driving performance versus a fixed camera. We expect that when we test the Stingray UGV in MOUT environments, head-aiming will be crucial for high-speed control.

## 5. HIGH-SPEED STINGRAY WARRIOR

In Phase II, we will modify the Stingray UGV to increase its maximum speed. The Warrior's standard drive train is designed to maximize torque in order to maximize payload capacity. Maximum torque comes at the cost of reduced top speed. During Phase II we will replace the high torque gears with high speed gears.

At high speeds, the high traction of the Warrior's treads becomes a liability, reducing vehicle speed and increasing power drain. Detracking – tracks separating from the drive wheels – also becomes a possibility at high speeds. For these reasons, our second modification will be to replace the Warrior's tracks and flippers with wheels. This should substantially increase the maximum effective speed of the vehicle.


Figure 5: High-speed Stingray Warrior UGV

The tradeoff is reduced ability to climb large obstacles and stairs. Without the flipper, the maximum forward offset of the articulated platform will also be reduced. However, we expect that the dynamic weight shifting behavior will be actually be more effective in altering handling characteristics, due to the reduced size of the ground contact patch for wheels (vs. tracks).

## 6. DRIVER ASSIST BEHAVIORS

We will develop a set of semi-autonomous driver-assist behaviors to help the operator control the Stingray UGV at high speeds. These behaviors will take commands from the OCU, process data from the sensors (LIDAR, GPS, INS), and send motion commands to the UGV.

Figure 6: Wayfarer PackBot performing autonomous perimeter following

We will be able to leverage and reuse much of the software we developed for the TARDEC-funded Wayfarer Project (Yamauchi, 2006). Figure 6 shows the Wayfarer PackBot performing autonomous perimeter following in an urban environment, using a combination of LIDAR and stereo vision for detecting walls and avoiding obstacles.

These behaviors will reduce the cognitive load on the operator and allow the operator to focus attention on the other tasks using the HARV. For example, the operator could order the UGV to drive down a street, while the operator scans the environment for potential threats. We expect this division of labor to greatly improve operator performance in reconnaissance and search tasks.

## 7. OBSTACLE AVOIDANCE

We will be reusing the obstacle avoidance behavior from the iRobot Mapping Kit. This behavior uses a randomized Monte Carlo algorithm for generating potential paths and then evaluates these paths based on behavior input and obstacle detection. The behavior provides a guarded motion capability that steers the vehicle in the direction commanded by the operator, if possible, but also steers around any obstacles in its path.

In addition, this behavior can be integrated with autonomous capabilities (such as perimeter and street following). In autonomous mode, the other behaviors supply desired motion commands, and the obstacle avoidance behavior attempts to follow these commands as closely as possible, while also swerving around any obstacles in its path.

## 8. PERIMETER AND STREET FOLLOWING

The perimeter and street following behaviors use the Hough Transform to detect the location and orientation of walls and street features. The Hough Transform is a computer vision technique that works by transforming image point coordinates into votes in the parameter space of possible lines. Each point corresponds to a vote for all of the lines that pass through that point. By finding the strongest points in the parameter space, the Hough Transform can determine the parameterized equations for the strongest lines in the image.

The Hough Transform processes range data from the LIDAR and calculates the strongest line orientations and offsets relative to the robot's current position. Our experiments showed that the system is highly accurate and reliable in determining the location and orientation of walls both outdoors and indoors.

We interfaced the Hough Transform line detector with a perimeter following behavior. The *follow-perimeter* behavior attempts to steer the robot so that it is parallel to the strongest line detected by the Hough Transform. To prevent the robot from oscillating between two lines that are approximately the same strength, an accumulator array is used to integrate the strength of line orientations over time. For computational efficiency, all lines with the same orientation vote for the same orientation, regardless of the range from each line to the robot. Orientations are grouped into 5 degree bins for a total of 72 bins.

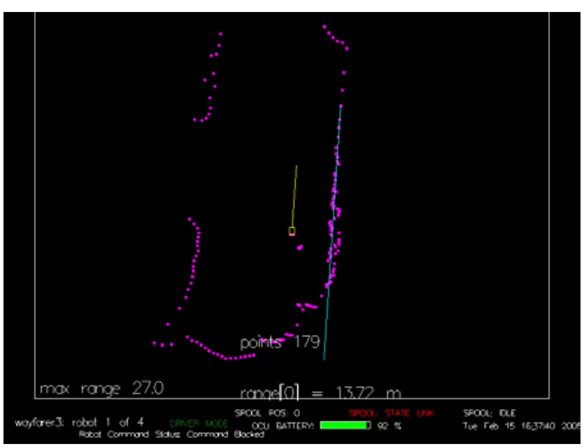


Figure 7: Hough Transform finds perimeter orientation

The *follow-perimeter* behavior outputs a desired absolute heading in world coordinates. This desired heading is passed to the obstacle avoidance system, which selects the obstacle-free heading that is closest to the desired heading output by *follow-perimeter*. This allows the robot to reactively steer around obstacles that are located next to walls and then resume wall-following automatically.

Our experiments showed that the Hough Transform works well to detect perimeter orientation even when the laser plane does not directly intersect the building wall. Figure 7 shows the Wayfarer PackBot following the raised landscape behind iRobot HQ. The yellow rectangle represents the robot's current position; the purple dots indicate LIDAR returns; and the blue line shows the wall orientation as determined by the Hough Transform. In this example, the laser plane intersects the grass and dirt of the landscape instead of the building wall, so the returned points are not perfectly aligned. Despite this, the Hough Transform is able to accurately determine the heading of the building perimeter.

The Wayfarer *follow-street* behavior is similar to the *follow-perimeter* behavior, but tracks lines on both sides of the robot.

## 9. DYNAMIC WEIGHT SHIFTING

The Warrior can radically change the position of its center of mass by moving an articulated platform forward and backwards. We will study the effect of platform position on the Warrior's handling. We will evaluate a range of different configurations in the range between the maximum backward and maximum forward positions. It is likely that the maximum forward position is unstable for the wheeled UGV, so we will determine the maximum stable forward position of the platform on this vehicle.

When a vehicle oversteers, its rear tires lose traction before the front tires, causing the vehicle to turn more than commanded. Vehicles with more weight on the rear wheels tend to oversteer more easily. When a vehicle understeers its front tires lose traction before the rear tires, causing the vehicle to turn less than commanded. Vehicles with more weight on the front wheels tend to understeer more easily. Vehicles that have roughly equal weight over both axles tend to have more neutral handling, meaning they that are less likely to oversteer or understeer, and that either oversteer or understeer can be triggered based on control inputs.

Understeer is almost always undesirable. However, a skilled driver can use oversteer to take turns faster than otherwise possible. The driver intentionally causes the rear wheels to break free, steers toward the exit point of the curve, and hits the throttle to break out of the slide. Done properly, this allows the vehicle to maintain more speed through the turn.

We will explore whether controlled oversteer can be used to increase the turn rate beyond what can be achieved without wheel slip. For these experiments, we will put the vehicle in the configuration that maximizes oversteer, and then we will determine whether we can take turns faster and/or sharper in this mode.

The results from these experiments will be used to design the dynamic handling behaviors for the Stingray UGV. These results will tell us what track and weight-balance configurations we should use for maximum speed in a straight line, for maximum turn rate, for maximum speed through turns, and for controlled oversteer. These behaviors will alter the Warrior platform position on the fly based on driver input.

For example, if the driver is commanding maximum speed in a straight line, the dynamic handling behaviors will put the vehicle into the configuration that was determined to maximize straight line speed. If the driver is commanding a hard right turn or hard left turn at low speed, the behaviors will select the configuration that minimizes the vehicle turn radius. However, if the driver is commanding a hard turn at high speed, the behaviors will select the configuration that maximizes speed through a sharp turn.

## 10. HEADING CONTROL

A small, lightweight UGV that drives at high speeds will spend a significant proportion of time in the air. This is especially true in rough off-road terrain, but even in urban environments, uneven road surfaces may result in a small, fast-moving UGV catching "air time". Our previous experience at both iRobot and Chatten with driving lightweight UGVs at high speeds shows that this is unavoidable for a vehicle with the weight (less than 100 kg) and speed (up to 40 kph) requirements for this project, unless it has a suspension that would add substantial weight, cost, and complexity to the vehicle platform. So instead of adding a heavy, expensive suspension to the small UGV platform, we will focus on maintaining control of the vehicle at high speeds despite the frequent loss of contact with the ground.

Our heading control behavior will allow the operator to specify a desired heading for the vehicle and command the vehicle to maintain that heading at a specified speed. We expect this to be particularly useful at high speeds when continuous, rapidly-changing steering inputs are required to maintain the vehicle heading if the vehicle loses contact with the ground and turns in the air. Like the perimeter following and street following behaviors, the heading controller will free the operator to focus attention on the surrounding environment instead of being distracted by driving the vehicle.

## 11. ENHANCED SITUATIONAL AWARENESS

Based on Phase I developmental work, it is clear that adding additional cameras as inset views into the main image of a head-aimed vision system can greatly increase situational awareness. Figure 8 (top) shows a 360° panoramic overlay on the main view. Figure 8 (bottom) shows a rear-view camera overlay on the main view.

With the 360° overlay, any motion in the panoramic image that is inconsistent with the motion of the remainder of the panoramic view will instinctively cue the operator's peripheral view processing to turn and look at the movement. Presenting image data this way to the operator takes maximum advantage of the operator's native visual processing. All of us instinctively process peripheral vision and automatically turn to look at movement in our periphery.

Similarly, the rear-view camera functionality takes advantage of operators' long-term experience with driving cars. Operators reversing the robot out of a tight passage will be able to use the main display to constantly look left and right to check side clearances, while using the inset image from the fixed rear-facing camera to gauge alignment and rear clearances.

We will modify our HARV to add five very small video cameras, of the type used in cell phones. Four of the cameras will be mounted at 90° spacing around the perimeter of the gimbal on the pan yoke ring, which moves with the pan axis. These four cameras will always have a fixed relationship with viewing angle of the main display. What is shown to the left in the panoramic image will be to the left of where the HARV is currently looking, and visa-versa. The fifth camera will be mounted in the base tube. This camera will face to the rear and slightly down, to provide a good view for backing up.

We will use low-power video processing electronics to merge the four 90° cameras together to create the panoramic image, and then overlay it on the NTSC video stream, without inducing any latency into the main video image. We will do the same thing for the single back-up camera image. We will also create a simple operator interface for selecting the different view modes.

Because high-speed teleoperation is so dependent on effective human-robotic interaction, testing with Army soldiers will be an important component of our development process. We plan to have a testable prototype of the enhanced situational awareness HARV early in Phase II, so that we can conduct testing of high-speed reconnaissance at the McKenna MOUT site at Fort Benning in 2009.

Figure 8: HARV main view with panorama (top) and rear view camera (bottom)

This early testing will be a quick reality check, looking at the issue of how soldiers might make use of a high-speed robotic reconnaissance platform, and what added functionality would be important to them. We will specifically get data and feedback on our enhanced situational awareness prototype.

## 12. LOW-LATENCY DIGITAL VIDEO

Vision is a critical teleoperation interface, but video requires very high communications bandwidth. In addition, video latency can critically impact mission performance and reduce operator effectiveness. The general figure of merit in the automotive simulation community is that visual latency needs to be below 100 ms in order for a car to be controllable.

Driving performance degrades with any measurable latency, and the level of performance impact gets steadily worse as latency increases. For this reason, we have used analog video and analog radios to transmit the video. However, the future of video transmission in the military is digital, so we will develop a digital protocol for our HARV system.

In Phase II, we will work within the existing H.264 digital video codec to create a low-latency, high-quality, low-bandwidth transmission protocol that is compliant with the H.264 spec and with military IP data radios. The video codec will use a technique that has been in the specification since H.261, but has never been implemented, except in academic research settings. This technique is sometimes called "distributed keyframing".

In digital video, a keyframe is a single, complete picture of a video frame, compressed in a similar fashion to a JPEG photo. Low latency digital video sends every video frame as a keyframe. As long as there is sufficient bandwidth, the result is good quality, high frame rate, and low latency. Military IP data radios, however, lack the bandwidth needed for this type of compression. The video is reduced to very low quality and low frame rates. The reduction in frame rate alone can cause the latency to exceed 100 ms.

Time and motion based compression schemes, such as MPEG-4, use P-frames that contain only incremental changes from the previous frame. A video stream can have the same apparent quality as the original analog image using periodic keyframes along with P-frames that are only 5% to 10% of the size of a keyframe (also called an I-frame). In high motion video, there may be one keyframe every second, which accounts for about half the bandwidth. The problem is that is a bandwidth-constrained environment, the keyframe would take a half second to transmit, causing at least a 500 ms latency in the video image.

The distributed keyframe technique breaks a single keyframe up into groups of "macroblocks". If there are 300 macroblocks in a video frame and 30 frames per second, then keyframe data for 10 macroblocks would be sent along with P-frame data for the other 290 macroblocks in each video frame. The result is an entire new keyframe each second, but only 17 ms of latency (due to keyframe transmission delays).

There are a number of other techniques that are also unimplemented in commercial adaptations of the H.264 specification that would help teleoperation in a bandwidth-constrained environment. The quality factor for the macroblocks in the center of the image can be set higher than in the periphery. Human vision works this way to reduce internal processing requirements in our visual cortex. By biasing quality to the center of the frame, the video bandwidth can be cut in half, without a perceptual difference to the operator. This is especially true when using head-aiming, where the operator naturally keeps objects of interest in the center of vision.

In macroblocks within the frame where there is motion that is counter to the overall image motion, the quality factor can be locally increased, which will make this moving object have sharper detail.

We can also make the video signal more robust and resistant to the types of signal drop-outs experienced in the field. The video can be double encoded, using a second low-resolution version behind the high-resolution video. If macroblocks within the high-resolution video are lost, then the low resolution will show through in those spots until new keyframe macroblocks can be used to fill in the detail.

When IP packets are dropped, we can avoid retransmitting the old packet, which can cause bottlenecks in the IP transmission. Instead, we can request an updated P-frame macroblock that skips over the lost data and provides the incremental changes from the last good data. When that P-frame data gets large, we can provide new keyframe data for the macroblocks instead.

Using these methods, our new digital protocol will enable the low-latency, high-quality, low-bandwidth video needed for immersive teleoperation.

## CONCLUSIONS

The Stingray Project is developing techniques for high-speed teleoperation of small UGVs. These techniques include immersive teleoperation and semi-autonomous driver-assist behaviors. In Phase I of this project, we integrated the Chatten Associates HARV with the iRobot Warrior UGV prototype, and were able to successfully drive the UGV through wooded terrain using immersive teleoperation. We also performed experiments with a high-speed man-portable surrogate UGV capable of speeds up to 30 mph (48 kph). Using immersive teleoperation, we were able to drive this UGV at high speeds through a slalom course.

In Phase II, we will develop a high-speed version of our Warrior. We will develop semi-autonomous driver-assist behaviors for obstacle avoidance, perimeter following, street following, dynamic weight shifting, and heading control. We will improve the HARV's situational awareness with additional cameras providing 360° degree panoramic views and rear-view insets. We will also develop a low-latency, high-quality, low-bandwidth digital video protocol for transmitting HARV video.

Finally, we will integrate all of these components to enable high-speed teleoperation of the modified Warrior in urban environments. We will test this system in MOUT environments and solicit feedback from warfighters on the best way to utilize these capabilities to meet current and future operational needs.

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