Robotic Modular Stereoscopic Retrofit System

Operational Field Assessment Report

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NATIONAL URBAN SECURITY TECHNOLOGY LABORATORY

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FOREWORD

The National Urban Security Technology Laboratory (NUSTL) is a federal laboratory organized within the U.S. Department of Homeland Security (DHS) Science and Technology Directorate (S&T). Located in New York City, NUSTL is the only national laboratory focused exclusively on supporting the capabilities of state, local, tribal and territorial first responders to address the homeland security mission. The laboratory provides first responders with the necessary services, products, and tools to prevent, protect against, mitigate, respond to and recover from homeland security threats and events.

DHS S&T works closely with the nation's emergency response community to identify and prioritize mission capability gaps, and to facilitate the rapid development of critical solutions to address responders' everyday technology needs. DHS S&T gathers input from federal, state, local, tribal and territorial first responders, and engages them in all stages of research and development—from building prototypes to operational testing to transitioning tools that enhance safety and performance in the field—with the goal of advancing technologies that address mission capability gaps in a rapid time frame, and then promoting quick transition of these technologies to the commercial marketplace for use by the nation's first responder community.

As projects near completion, NUSTL conducts an operational field assessment (OFA) of the technology's capabilities and operational suitability to verify and document that project goals were achieved.

NUSTL's publicly released OFA reports are available at: https://www.dhs.gov/publications-library/collections/science-and-technology. OFA reports deemed sensitive are available on a case-by-case basis and can be requested by contacting NUSTL@hq.dhs.gov.

Visit the DHS S&T website, www.dhs.gov/science-and-technology/first-responder-technologies, for information on other projects relevant to first responders.

Visit the NUSTL website, www.dhs.gov/science-and-technology/national-urban-security-technology-laboratory, for more information on NUSTL programs and projects.

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EXECUTIVE SUMMARY

The Robotic Modular Stereoscopic Retrofit (MSR) System was designed by Honeybee Robotics with support from the U.S. Department of Homeland Security's (DHS) Science and Technology Directorate (S&T). The MSR is a vision system for bomb disposal robots that provides a remote operator with stereoscopic imagery for improved depth perception and robot manipulation assistance.

Bomb robots are used to inspect and manipulate suspect packages or explosives and are controlled by operators from a safe standoff distance. Operators rely on robot vision systems for video imagery to control the robot, its manipulator arm and its gripper. The MSR aims to improve an operator's perception of the robot's environment by providing a real-time, high-resolution, three-dimensional image without the need for headsets or special glasses. The MSR is composed of a camera module, a power and data transmission core module, and an operator control station (OCS) with lenticular display. The MSR is modular, platform-agnostic, and built with commercially available components to be an affordable option for retrofitting existing robots. The camera modules can also be installed on various locations on the robot for different mission scenarios.

S&T's National Urban Security Technology Laboratory (NUSTL) conducted an operational field assessment (OFA) on September 22, 2021, during which five experienced bomb technicians evaluated the system at the Middlesex County Fire Academy located in Sayreville, New Jersey. Evaluators installed individual MSR systems on three different robot platforms (i.e., an Icor MK3, an Icor T5, and a Telemax Hybrid) and operated the system under daylight, lowlight and extended distance conditions.

The evaluators readily adapted to using the MSR system for stereoscopic imagery and favorably rated its depth perception capability. They considered the camera's image quality an improvement over existing robot cameras. They made suggestions for improving the usability of the display screen in bright sunlight conditions and for mounting the MSR components on the robots. During the OFA, the MSR systems' video lagged and failed when the robot moved beyond approximately 150 to 250 feet from the control station and when the robot went into or behind a concrete block building. Evaluators stated that the wireless transmission capability of the MSR must be improved so that the MSR will operate wherever the robot can operate.

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1.0 INTRODUCTION

Bomb technicians protect the public by rendering explosives safe and performing forensic work on those explosives. Mobile, unmanned platforms (i.e., bomb disposal robots) are controlled by operators from a safe standoff distance. Bomb technicians rely on robot vision systems for video imagery to control the robot, its arm, and its gripper for manipulation of devices or tools. Existing robot vision systems, however, are limited to two-dimensional images.

As a result, the Department of Homeland Security's (DHS) Science and Technology Directorate (S&T) awarded a contract to Honeybee Robotics to develop the Robotic Modular Stereoscopic Retrofit System (MSR). This system aims to improve an operator's perception of the robot's environment by providing real-time, high quality, stereoscopic video imagery using camera heads, a power and data transmission core module, and an operator control station (OCS) with a glasses-free lenticular display. The display creates the perception of 3-dimensional depth of the environment or an object of interest. The MSR is platform-agnostic and built with commercially available components to be an affordable option for retrofitting existing robots.

On behalf of the S&T Office of Mission and Capability Support (MCS), the National Urban Security Technology Laboratory (NUSTL) conducted an operational field assessment (OFA) to evaluate the suitability of the MSR for use by bomb technicians. NUSTL conducted the OFA at the Middlesex County Fire Academy located in Sayreville, New Jersey. MCS and Office of Science and Engineering (OSE) program management staff observed remotely over Microsoft Teams. This report describes the evaluators' feedback obtained during the operational test activities that simulated conditions one might encounter during emergency response missions.

1.1 Purpose

The purpose of the OFA was to assess the suitability of the MSR for bomb technicians in a simulated operational environment.

1.2 Objectives

The OFA assessed MSR performance related to:

- **Deployability**, which includes the ease and speed of setting up the system, the ability to install it on multiple robot types, and the system's suitability in operational environments
- **Capability to provide multiple camera views**, including a stereoscopic view at distances up to 500 feet away (robot to operator control) and the effectiveness of that stereoscopic view
- **Usability,** defined as ease of use, accuracy, handling quality, and performance
- **Conformity**, that is, whether the MSR meets design requirements

1.3 Participants

Table 1-1 lists the OFA participants. Five evaluators from four agencies participated, along with NUSTL's OFA team, the technology developer and a variety of observers.

Table 1-1 OFA Participants

Role	Organization
Evaluators	New Jersey State Police Bethlehem Pennsylvania Bomb Squad Federal Bureau of Investigation, New York City, New York Federal Bureau of Investigation, Newark, New Jersey
Venue Host	Middlesex County Fire Academy, New Jersey
Program Managers and Support Staff	U.S. Department of Homeland Security, Science and Technology Directorate (through Microsoft Teams)
OFA Test Director and Data Collectors	U.S. Department of Homeland Security, Science and Technology Directorate, National Urban Security Technology Laboratory
Technology Developer	Honeybee Robotics Inc.
Observers	New Jersey State Police Metro North Railroad NYSTEC (New York State Technology Enterprise Corporation)

1.4 Requirements

Table 1-2 summarizes requirements that the MSR was expected to meet and the manner by which those requirements were tested during the OFA. Test requirements were drawn from the contract's statement of work [1] and the "Gap Comparison" spreadsheet [2], both of which identify critical capabilities for functionality. The requirements in this matrix have been reviewed and validated by the S&T MCS program manager.

Table 1-2 Modular Stereoscopic Retrofit System Requirements

Category	No.	Requirement	Assessment Method
Installation	1	Installation and start-up of the system is rapid.	Evaluators install and set up the system and provide feedback on the speed and ease of installation. The system installation process is timed for reference.
	2	System installation does not require modification of the robot platform.	Evaluators mount the cameras and core module on the robot and confirm no permanent modifications are necessary.
	3	The system can be installed on multiple types of robots (i.e., platform-agnostic).	Evaluators assess the system on two or more different robots. Evaluators also provide opinions on whether the system can be installed on additional types of robots.
	4	The camera head is field-poseable.	Evaluators assess the ease of field-positioning of the camera head.
	5	Core module mounting does not impact robot performance.	Evaluators mount the module with or without the use of Picatinny rails and confirm that robot performance is not impacted.
Camera and Display	6	The camera modules have a wide field of view.	After using the system, responders are asked if the field of view is sufficient.
	7	Multiple cameras mounted in various positions on the robot produce multiple video feeds.	Evaluators examine both monocular and stereoscopic views from the cameras as well as the camera zoom. They also toggle between video feeds from two camera modules in different locations on the robot and confirm that they have multiple points of view.
	8	The system displays a high-fidelity representation of object colors.	Evaluators assess whether the display of object colors supports differentiating elements of the device.
	9	The system will not distort the perception of form and shape of target objects.	After using the system, evaluators are asked if the image appears free from distortion and enables adequate perception of form, shape, depth and distance to differentiate and separate elements of the device. Evaluators attempt to estimate distance and to read labels or icons on the target device.
	10	The operator control station display has sufficient brightness.	Evaluators assess whether the display that is set up outdoors in direct sunlight conditions is sufficiently bright to perceive all images for inspection and manipulation tasks.
	11	The operator control station can be adequately viewed when used in broad daylight.	Evaluators assess use of the display in bright daylight conditions with and without a sunshade.
	12	Camera modules incorporate dimmable LED arrays and petal hoods for illumination and glare shading in low light and bright light conditions.	Evaluators assess whether the cameras provide adequate display imagery when the robot is in both low light and bright light conditions.

Category	No.	Requirement	Assessment Method
Comms/ Range	13	The remote and operator segments will continue to operate when separated by a distance up to 500 ft.	Evaluators assess the performance of the wireless link when the robot is deployed 500 feet away (line of sight) from the operator control station by noting any loss of communication or degradation of the display image.
General	14	The system is intuitive to operate.	Evaluators perform a series of inspection and manipulation tasks aided by the camera system. They are asked if the system meets their expectations for ease of use/intuitiveness to operate.
	15	The system will be rugged.	Evaluators operate the robot and MSR in operational tasks on mixed terrain (e.g., pavement, grass, curb) and are asked whether they believe that the system is rugged enough for their use cases.
	16	Operation of the system will not cause discomfort to the operator (e.g., eye strain, headaches)	Evaluators note whether viewing the stereoscopic display causes them any visual discomfort. Evaluators assess the image stability and whether the display is free from flicker. Evaluators assess whether the need to constrain their head movement for stereoscopic viewing causes discomfort.
	17	The system is an improvement over existing camera systems on robots.	After using the system, evaluators are asked if the system would improve their operations.

1.5 System Description

The MSR is a modular, platform-agnostic system for retrofitting existing bomb robots. It is designed to improve the view of the robot's environment through multiple camera angles and stereoscopic views. The system is comprised of three main components: a camera head, a power and data transmission core module, and an operator control station (OCS) with glasses-free lenticular display (Figure 1-1). The core module and up to three camera heads attach to the robot without requiring any permanent modification to the platform.

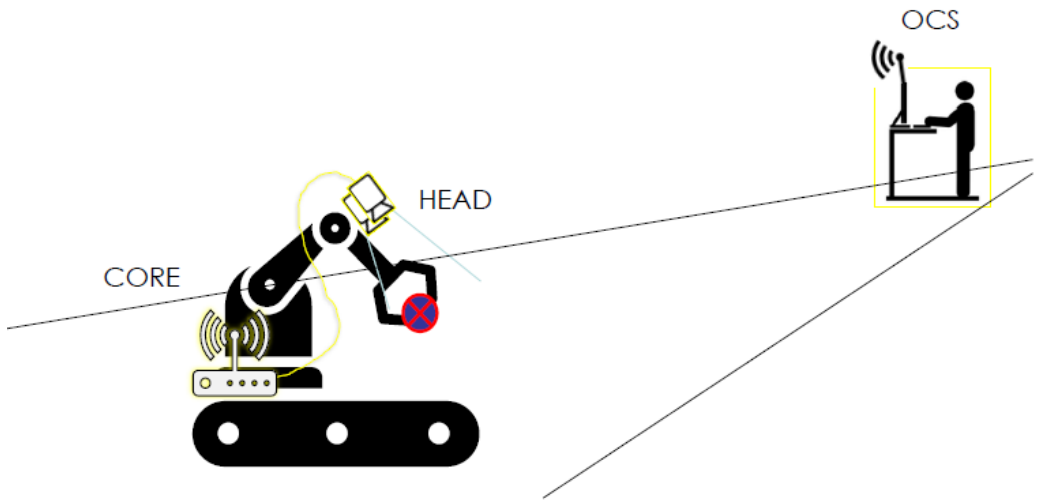

Figure 1-1 Robotic MSR System

Image Credit: Honeybee Robotics

The camera head is designed to fit within a 3.25" X 3.25" X 5.375" area. It consists of a near-view stereo camera pair, a wide-view stereo camera pair, LED lights for illumination, and a StereoPi interface board, with integrated Raspberry Pi CM3+ single board computer for processing. Power and Ethernet connections are provided to the camera head from the core module via a custom cable. Each camera pair consists of two Sony IMX219 8.08 MP CMOS image sensors[1]. These sensors have a total resolution of 3296 x 2480 pixels but are used at 1920 x 1080 pixels to reduce latency. The cameras are connected to a camera multiplexer that allows the user to switch between the two camera pairs. The camera signal enters the StereoPi board where the Raspberry Pi encodes it according to the high definition video compression standard (H.264) [3] for transmission to the core via the Ethernet interface. The camera head also has an onboard voltage regulator, allowing it to accept voltages from 7 to 37 volts.

[1] CMOS (complementary metal oxide semiconductor) image sensors are camera components that convert light into electrical signals.

Figure 1-2 (clockwise from top left) Camera Head, Core, Installed System, OCS
Image Credit: Honeybee Robotics

The core module handles battery management and wireless communications. It consists of a BotBlox Ethernet switch, a Doodle wireless radio, and a battery pack. The MSR as tested used a 12-volt 6-amp-hour lithium-ion battery to meet performance requirements. The system can accept voltages from 10 to 30 volts, so other power sources could be substituted if desired. The BotBlox switch connects the core with the camera head modules via the custom connectors. The Doodle wireless radio is an industrial Wi-Fi transceiver. In the standard setup, it works as a point-to-point link between the core and the OCS, though it can also be configured to connect to an existing Wi-Fi network.

The operator control station consists of a lenticular display, ruggedized laptop, and a Doodle radio. The lenticular display allows the operator to view the stereo camera footage as a three-dimensional image without the need for special glasses or goggles. The Doodle radio receives the video from the core module. The laptop performs all the processing necessary to render the stereoscopic video on the lenticular screen. It also runs the control software for the system, providing a user interface to monitor system status, switch between camera views, etc. The lenticular screen is held by a monitor arm attached to a tripod, allowing the user to position it appropriately while still using the existing control setup to operate the robot.

2.0 OPERATIONAL FIELD ASSESSMENT DESIGN

2.1 Event Design

During this OFA, five evaluators from the New Jersey State Police, Bethlehem Pennsylvania Bomb Squad and the Federal Bureau of Investigations assessed the MSR's capability to provide enhanced camera views, as well as its usability, and deployability. The NUSTL OFA team gathered evaluator feedback in order to validate the MSR's conformity to technical requirements. During the OFA, evaluators participated in various activities at three operational control stations. The MSR was assessed in daylight and low light conditions, as well as extended distances. Observers from NYSTEC, Metro North Railroad and the NJ State Police watched the OFA activities in person; S&T program management staff observed remotely over Microsoft Teams.

Evaluators were grouped into three teams with data collectors from NUSTL assigned to each. The data collectors facilitated the test activities as well as recorded observations and comments during them. Upon completion of each station's activities, NUSTL gathered feedback from the evaluators using a questionnaire. After all activities had been completed, the NUSTL OFA team solicited additional feedback from the evaluators during a group debrief session.

2.2 Scope

The OFA consisted of a presentation and technology familiarization session, three sets of assessment activities, and a debriefing session.

2.2.1 Classroom Presentation and Technology Familiarization

The OFA began with an introductory session providing evaluators with an overview of the OFA process, how S&T identified the capability gap, and a summary of the planned activities. In the classroom, Honeybee Robotics provided an overview of the MSR that included background on the development of the technology and a familiarization session. During this session, evaluators were able to ask questions about the technology.

Figure 2-1 Evaluators listen during the technology familiarization session

2.2.2 Assessment Activities

After the technology familiarization session, the evaluators – divided into three teams and working simultaneously – performed the activities listed in Table 2-1. The teams used three different robot platforms: the Icor MK3, the Icor T5, and the Telemax Hybrid (Figure 2-2).[2] After completing the activities for each station, evaluators provided responses to direct questions from NUSTL data collectors. The NUSTL team also made note of any relevant observations and comments evaluators made during the activities.

Table 2-1 Robotic MSR System OFA Activity Descriptions

Activity Title	Activity Description	Purpose
Installation	The evaluators observed as Honeybee Robotics demonstrated the setup procedure for the OCS. Each evaluator team then installed the MSR components onto a robot platform and drove the robot a short distance while actuating the robot arm to verify the installation procedure.	These activities assessed the quickness and ease of component installation, the ability to install on multiple robot types with no modifications to the platforms, and verified that the MSR does not negatively impact robot performance.
Daylight Operation	Evaluators drove the robots to an outdoor activity station under daylight conditions. They then utilized the MSR's camera to perform manipulation tasks such as opening a zipper and grasping an object from inside a container. The evaluators also attempted to read small print on a label.	These activities assessed the readability of the display in daylight conditions, the ability to estimate distances, distinguish colors, and present the form and shape of objects without distortion, and to do all this without users experiencing any visual discomfort while using the system.
Low-Light Operation	Evaluators maneuvered the robots into a dimly-lit indoor activity station. They attempted to use the MSR's camera and LED lighting arrays to perform inspection and manipulation tasks on target objects. However, once inside the building, the OCS lost radio communication with the core module, which prevented the evaluators from completing the assigned tasks.	These activities attempted to assess the ability of the camera and LED array to function in low-light conditions, to estimate distances and distinguish colors, to present the form and shape of objects without distortion, and to do all this without users experiencing any visual discomfort while using the system.
Extended Distance Operation	Evaluators attempted to drive the robots over rough pavement to an outdoor activity station 500 feet from the OCS and perform manipulation tasks on target objects. However, the OCS lost radio communication with the core module at a distance of about 200 feet, which prevented the evaluators from completing the assigned tasks.	These activities assessed the ability of the MSR system to function at a distance of 500 feet, the ruggedness of the mounting method for the camera and core module, and the ease of use of the system.

[2] Full details of the event design are described in the "Robotic Modular Stereoscopic Retrofit System Operational Field Assessment Plan." [4]

Figure 2-2 Icor MK3, Icor T5, and Telemax Hybrid Robot Platforms

2.2.3 Debrief

The NUSTL OFA test lead facilitated a debriefing session with all OFA participants at the conclusion of the activities. During this session, evaluators provided comments that elaborated on their numerical ratings of different requirements.

2.3 Limitations of and Deviations from the Test Plan

2.3.1 Limitations

The assessment was limited by both resources and practicality in several ways. Testing took place at a firefighting training facility, with low-light operations taking place in a solid concrete structure. This had a negative impact on wireless system performance in testing compared to how the system would likely perform in typical wood frame residential construction even with a brick exterior, as concrete attenuates wireless signals more than brick and significantly more than drywall [5].

Limitations on the assessment of each criterion are detailed in Table 2-2 below.

Table 2-2 Limitations on Assessment of Requirements

No.	Requirement	Limitations
1	Installation and start-up of the system is rapid.	Installation of the MSR was carried out by novice users on specific robots under supervision of the technology developer. Results may vary based on the type of robot platform, attachment method, and user experience level.
2	System installation does not require modification of the robot platform.	A variety of attachment strategies were available for different robot types. Results are based on the specific robots and attachment strategies used in this OFA.
3	The system can be installed on multiple types of robots (platform-agnostic).	Due to resource constraints limiting the number/types of robots available for test, not every single type of robot installation can be verified. Positive results cannot guarantee every single robot installation.
4	The camera head is field-poseable.	The ability to adjust camera pose depends on the camera location on the robot and the attachment method. Limited scenarios will be tested, and results may not apply to different robots, camera locations, or attachment methods.
5	Core module mounting does not impact robot performance.	Due to the limitation of using a few specific robot types, not every type of robot installation can be verified. Also, all possible robot maneuvers/actions could not be tested during this OFA.
6	The camera modules have a wide field of view.	Evaluators will examine monocular and stereoscopic views as well as the camera zoom during specific assessment tasks. Sufficiency of the field of view is based on the specific tasks completed and the opinions of the participating evaluators.
7	Multiple cameras mounted in various positions on the robot produce multiple video feeds.	N/A. System developer did not provide additional cameras so this could not be assessed at the OFA.
8	The system displays a high-fidelity representation of object colors.	Resource constraints limited the amount of test objects and lighting conditions available for the OFA.
9	The system will not distort the perception of form and shape of target objects.	Resource constraints limited the amount of test objects and lighting conditions available for the OFA.
10	The operator control station display has sufficient brightness.	Results are based on a limited number of evaluators using the system in limited duration daylight conditions.
11	The operator control station can be adequately viewed when used in broad daylight.	System operation occurred at a set date and time and was limited to the corresponding daylight conditions. Results may vary for different times of the day and year and for differing weather and environmental conditions.

No.	Requirement	Limitations
12	Camera modules incorporate dimmable LED arrays and petal hoods for illumination and glare shading in low light and bright light conditions.	Resource constraints limited the amount of time and lighting conditions available for the OFA; results may differ for other conditions.
13	The remote and operator segments will continue to operate when separated by a distance up to 500 ft.	The wireless link performance was assessed as a line of sight, outdoor measurement at this specific time and location. Results may vary for different site conditions that may include physical obstructions or radio frequency interference.
14	The system is intuitive to operate.	The system was assessed by a limited group of evaluators in a limited time frame. The same results cannot be guaranteed for additional evaluators carrying out additional activities over an extended timeframe.
15	The system will be rugged.	Due to resource constraints and limited time, all possible robot activities and operating conditions could not be tested during this OFA. Other users may also have differing needs from the evaluators represented in the OFA.
16	Operation of the system will not cause discomfort to the operator (e.g. eye strain, headaches).	Results for operator comfort are based on a limited number of evaluators using the system for limited time and may not reflect the experiences of additional evaluators using the system for extended time periods.
17	The system is an improvement over existing camera systems on robots.	Results are based on a small sample of evaluators using the system for specific tasks in limited activities and may not reflect the experience of all users in additional scenarios.

2.3.2 Deviations

Test procedures had minor deviations from the Robotic Modular Stereoscopic Retrofit Operational Field Assessment Plan. [4]

- Due to time constraints, the training on installation and the “installation by operator” portions of the OFA plan were combined. Evaluators assisted and watched the developer install the system on the robots, rather than watching the developer do it once, then uninstalling the systems and reinstalling them by themselves. Evaluators stated this change of plan would not impact their assessment of the installation criteria (Requirement 1).
- Because the developer brought a single camera head per system, evaluators could not assess the criterion related to multiple cameras and video feeds (Requirement 7).
- Due to wireless signal issues, low-light operations were limited. Evaluators were able to move the robots into the indoor environment, but full navigation in low light was not performed (Requirement 9).
- Due to the layout of the facility, there was no option to travel 500 feet in a straight line for the extended distance operation test (Requirement 13).
- Since the system was not functional at that range, operators did not perform tasks at the extended range (Requirement 13).

3.0 RESULTS

This section contains evaluators' feedback gathered from questionnaires and group discussions. The technology requirements (Table 1-2) guided the assessment activities and have been grouped into the categories of installation, camera and display, communications and range, and general ability. The NUSTL OFA team prompted the five evaluators with a statement related to an activity they performed, and the evaluators selected a response of strongly agree, agree, neutral, disagree or strongly disagree with that statement. Appendix Table 5-1 summarizes the evaluators' responses to each statement. Evaluators also provided comments to explain their ratings. Relevant comments from the end-of-day group discussion are also included here.

3.1 Installation

This section covers the evaluators' assessment of the installation procedure, including the quickness and ease of installation, the ability of the system to be installed on multiple types of robots, and the ability to adjust the camera head position after installation. Figure 3-1 shows the evaluators' ratings for statements related to these installation activities. The number in square brackets after the statement represents which requirement number from Table 1-2 it addresses. Sections 3.1.1 through 3.1.3 further describe the ratings.

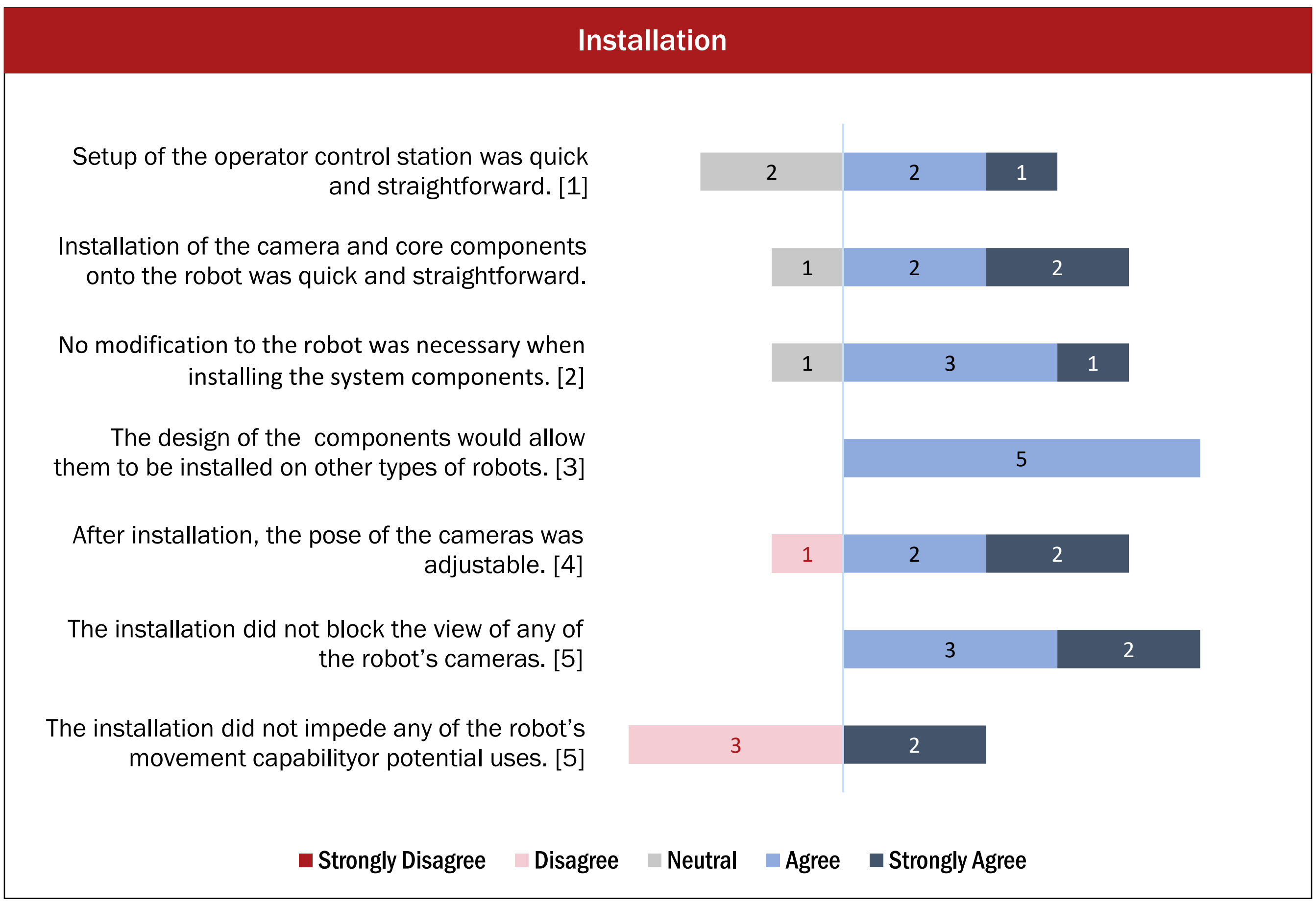

Figure 3-1 Evaluator Ratings of Installation Activities

3.1.1 Component Installation and System Setup

At the OFA, the developer set up the OCS while the evaluators installed the camera and core module on the robots. Regarding the OCS setup, three evaluators agreed or strongly agreed that the procedure was relatively quick and straightforward. Two evaluators were neutral; one of these evaluators stated that while the developer did the actual setup, it did not appear to be any more difficult than setting up a laptop, monitor and tripod. Another evaluator noted that according to the developer the laptop is only needed for the prototype, so he felt the setup would likely be easier for the commercial version.

The developer presented a training for the component installation procedure before the evaluators installed the components. Four out of five evaluators agreed or strongly agreed that the training was sufficient for them to perform the installation. One was neutral. One evaluator stated that demonstrating the procedure on an actual robot would have been more useful than the training presentation. Another said that he felt the training could be reproduced.

The evaluators installed the MSR components on to three different types of robots. When asked if this procedure was “quick” and “straightforward,” four evaluators agreed or strongly agreed, while one was neutral. One evaluator said that the installation was fairly quick once he figured out where to install the components. Another stated that the procedure was not quick, and the setup might take too long depending on the situation.

3.1.2 Modular Design

When asked to respond to the statement, “No modifications to the robots were necessary when installing the system components,” three evaluators agreed, one strongly agreed, and one was neutral. One evaluator noted that additional Velcro straps had to be added in order to hold the components securely in place—that is while not a “modification,” it would be helpful to simply have more of what the developer had already supplied. Another suggested that the developer use Picatinny rails or GoPro mounts instead of Velcro straps in future versions to improve the stability of the component mounting.

All five evaluators agreed that the MSR camera and core module could be installed on multiple types of robots. One evaluator stated that he was not familiar with many robot types, but felt that it would be possible to install the MSR on multiple platforms. Another evaluator offered that the developer should consider using a 3D printer to customize the mounting brackets for a wider variety of robots.

3.1.3 Effect on Robot Performance

After component installation, the OFA team asked evaluators to verify that the pose of the camera was adjustable. Four evaluators agreed or strongly agreed with that statement, while one disagreed. Two evaluators stated that although the camera pose was adjustable during installation, it was fixed in a position after that and that could not be readjusted during deployment.

All five evaluators agreed or strongly agreed that the component installation did not block the view of any of the robot’s cameras. When asked to verify that the installation did not impede any of the robots’ movement capabilities or limit its potential uses, two evaluators agreed while three disagreed.

Those who disagreed noted that the video/data cable linking the camera head and core module could become disconnected, be damaged, or pull the camera off of its mounting while the robot arm rotated. This comment was specific to the Telemax Hybrid robot, which features an articulating arm that can rotate two or more full turns in one direction.

3.2 Camera and Display

This section covers the evaluators' assessment of the camera, display, and stereoscopic imagery in different lighting conditions. Figure 3-2 shows the evaluators' ratings for statements related to the MSR camera and display. The number in square brackets after the statement represents which requirement number from Table 1-2 it addressed. Sections 3.2.1 through 3.2.5 further describe these ratings.

Overall, the review of the camera and display was positive. Evaluators found the quality of the MSR camera's image excellent and superior to the robots' onboard cameras. They considered the depth perception offered by the stereoscopic view helpful. Evaluators noted some difficulty, however, with viewing the screen in bright daylight conditions but felt the difficulty could be overcome by moving the operator control station inside a vehicle.

Throughout the assessment the video lagged, that is, the video image from the MSR lagged behind images from the robots' onboard cameras. The lag increased when distance between the robot and OCS increased and when the robot went within or behind a building. This limitation prevented evaluators from being able to complete some planned activities yet still yielded important information relevant to test plan criteria. Feedback on individual criteria are described below.

3.2.1 Camera View

All five evaluators agreed or strongly agreed that that the MSR provided a sufficient field of view. Only three evaluators responded to statements regarding the monocular view and camera zoom because those capabilities were assessed during the low-light activity session, which not all evaluators were able to complete. Out of three responses, two evaluators agreed and one strongly agreed that the MSR's monocular view is an improvement over the existing robots' camera views. Both evaluators who answered "agree," mentioned the video lag was detrimental, but that otherwise the view was clear and offered an improved visual experience. All evaluators who responded agreed that the MSR's camera zoom was sufficient for their uses. One evaluator remarked that it would be useful to have more than three levels of zoom.

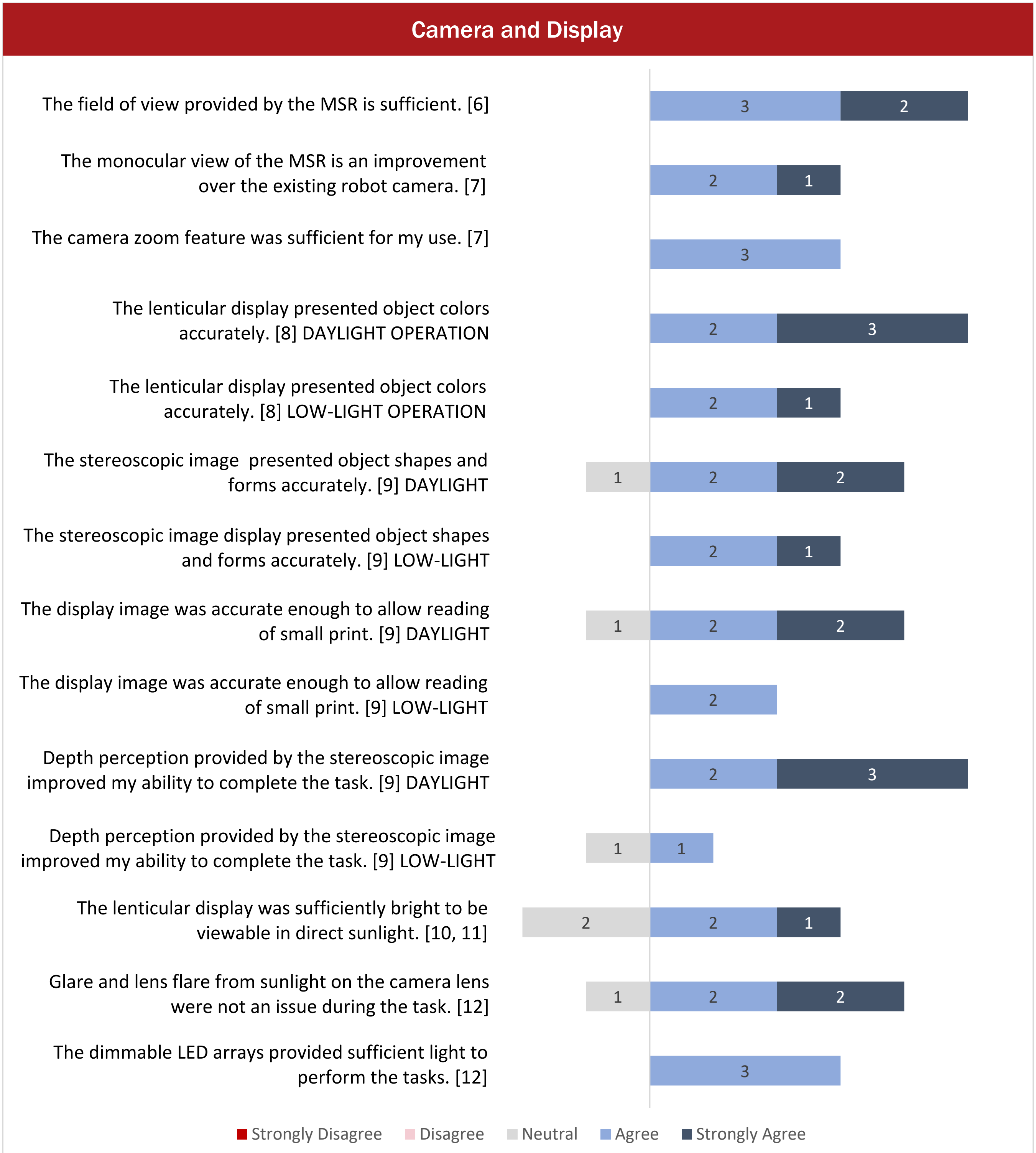

Figure 3-2 Evaluator Ratings of Camera and Display

3.2.2 Image Accuracy

All evaluators agreed or strongly agreed that the MSR represented colors accurately in both daylight and low-light activities.[3] Evaluators commented that the MSR camera offered higher resolution and clearer colors than the robots' onboard camera systems.

Most evaluators agreed or strongly agreed that the MSR's stereoscopic imagery was accurate in shape and form and free from distortion. In daylight conditions, two evaluators agreed, two strongly agreed, and one gave a neutral response. In low lighting, two of three respondents agreed and the other strongly agreed. One evaluator noted that the image was of high-definition quality once his head was positioned properly to view the stereoscopic image, a reminder that operator position affects how the images are perceived regardless of how they are presented by the MSR. The evaluator who selected the neutral rating stated that the video lag made it hard to tell if the image was distortion-free and presented object shapes and forms accurately. Indeed, multiple evaluators pointed to problems with video lag and screen glare while rating this criterion.

Four evaluators agreed or strongly agreed that small print could be read using the MSR. One evaluator commented that the image is much better than the robot's camera. Another remarked that he could see numbers on the prop's electronics breadboard and read a resistance value on a circuit board. The evaluator who rated this criterion as neutral explained that the inspection task he selected did not contain any print to read.

3.2.3 Depth Perception

Most evaluators agreed or strongly agreed that the depth perception provided by the stereoscopic image was helpful. One evaluator noted that the stereoscopic image helped him determine depth when the robot's gripper was close to an object. One evaluator rated this criterion neutral, saying he could not assess it during the low-light task because of excessive video lag time.

3.2.4 Display Brightness

Regarding using the MSR's display screen in daylight, evaluators' ratings varied from neutral to strongly agree that glare was not an issue (2 agree, 2 strongly agree, 1 neutral) and for whether the display was sufficiently bright for use in direct sunlight (2 agree, 1 strongly agree, 2 neutral). Although the day of the OFA was not fully sunny, evaluators remarked on glare from sunlight and having some difficulty viewing the display screen. One evaluator noted he could see his own reflection in the screen and that made viewing the image more difficult. Multiple evaluators suggested using a sunshade hood over the screen or putting the OCS inside a vehicle could likely resolve these challenges.

3.2.5 Supplemental Lighting

The three evaluators who performed the low-light condition activity agreed that the LED arrays integrated into the camera module provide sufficient lighting to perform tasks. One noted that the MSR's light is stronger than the robot's light.

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[3] Because some evaluators were unable to complete indoor activities, the number of responses for activities in low lighting are less than for the same activities in daylight conditions.

Another commented that the LED light "made it look like daylight," but struggled to assess the criterion because the video lagged and froze during the task.

3.3 Communications and Range

This section covers assessment of the wireless performance of the system, in particular whether the remote and operator segments continue to operate when separated by a distance up to 500 feet.

All evaluators experienced challenges with the wireless video system in both the indoor, low light scenario and the extended distance scenario. In the indoor, low light scenario, the system initially lost connection while navigating in the building. The system and props being used in the scenario (simulated explosive devices) were moved closer to the door to reduce the number of walls the signal had to travel through. After that, the system did not lose connection, but a transmission delay (the aforementioned "video lag") still prevented evaluators from effectively using the system as intended. One evaluator summarized the experience saying, "The camera is great. It's the lag that's difficult to deal with."

Multiple factors could explain, or have played a role in, the diminished transmission range and speed of the system. One possible cause might have been a congested Wi-Fi spectrum, either from running three MSR systems close to each other or because of interference from other Wi-Fi devices present. Another potential cause is concrete construction of the building used to stage in the low light assessment. It is also possible that the selected radio was simply not powerful enough to meet the criteria.

Overall, the communications and rage of operation criteria were not met by the system. All three evaluators who performed the range tests disagreed or strongly disagreed with the statement "the system was able to operate at a range of 500 feet" (Figure 3-3). The technology developer noted that performance of the communication system at the OFA did not match their previous testing and said Honeybee would investigate possible causes and improvements to the system.

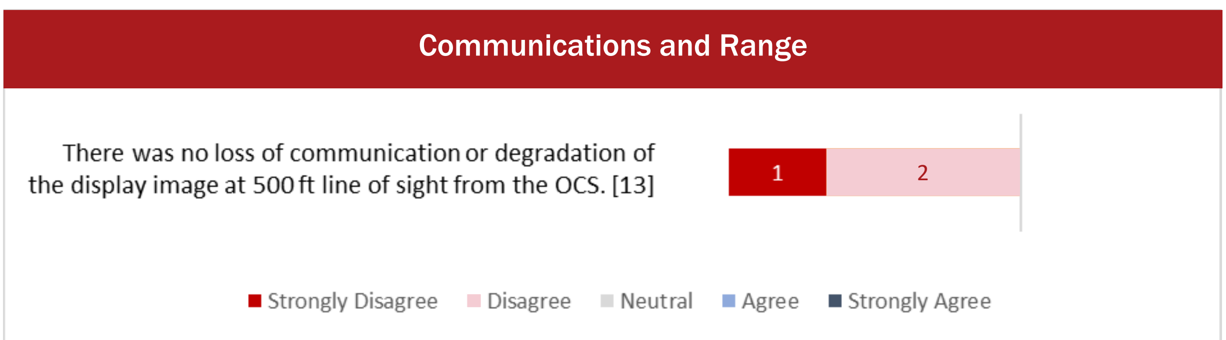

Figure 3-3 Evaluator Ratings of Communications and Range

Some evaluators suggested that using a wireless mesh mobile ad hoc network (MANET) radios on licensed spectrum, rather than relying on ISM band Wi-Fi might solve the problem of extending the MSR's wireless range. Nonetheless, others pointed out that such systems are often very expensive and may be outside the budgets of smaller departments.

3.4 General Usability

This section covers the evaluators' assessment of the general usability of the MSR system, including ease and comfort of use and comparison against existing robot camera systems. Figure 3-4 shows the evaluators' ratings. Sections 3.4.1 through 3.4.4 further describe these ratings. Suggestions for improvement that NUSTL's OFA team gathered during the group discussion are also described.

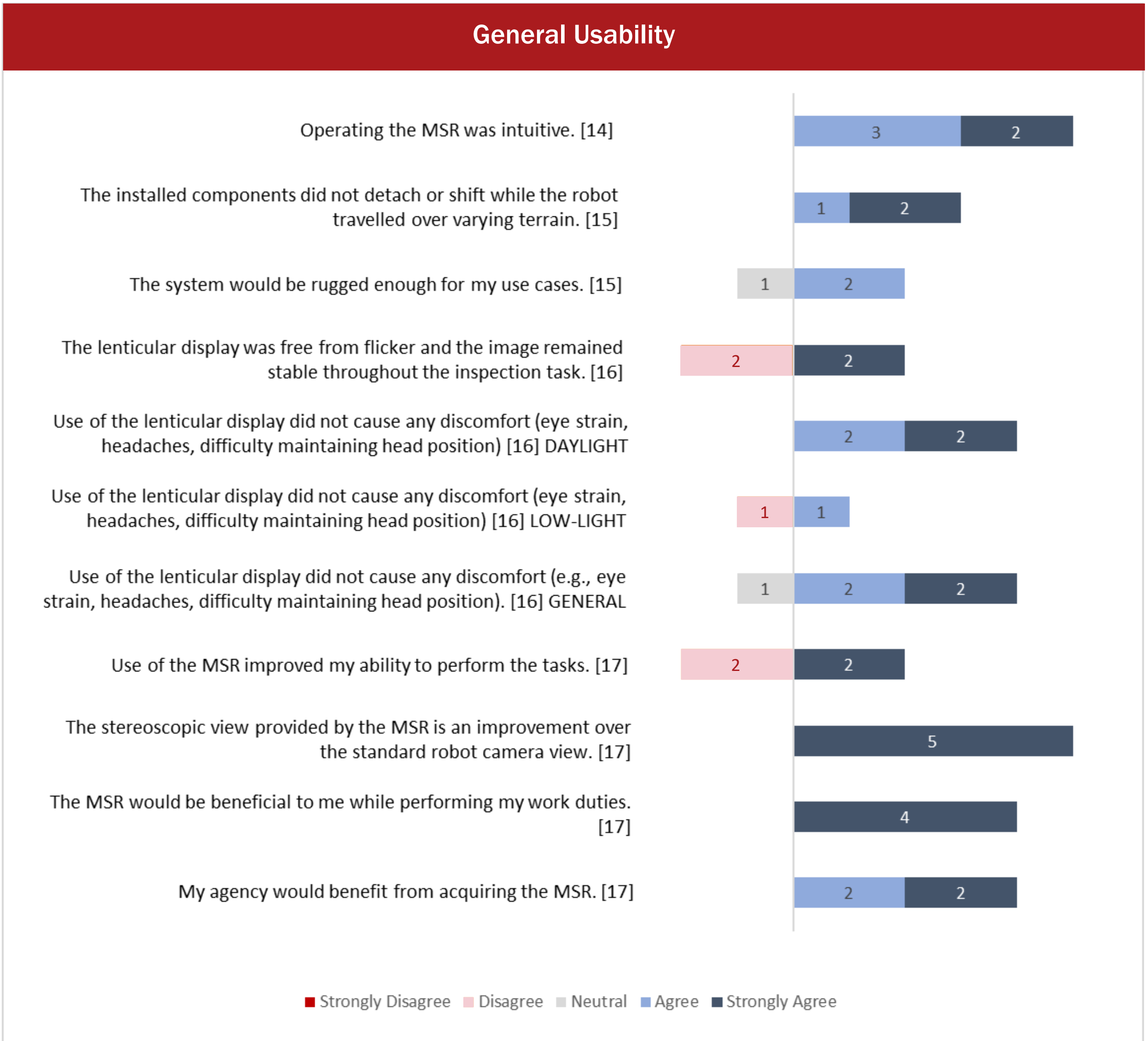

Figure 3-4 Evaluator Ratings of General Usability

3.4.1 Ease of Use

Evaluators were asked if the training provided by the developer was sufficient to learn to operate the system: three evaluators agreed and two strongly agreed. One evaluator recommended having an MSR system in the classroom for demonstration purposes in addition to the training presentation.

Another evaluator recommended that the training include scenarios. When asked if operating the system was intuitive, three evaluators agreed and two strongly agreed. One evaluator said that the display takes some getting used to in order to find the “sweet spot” where the image appears in 3D. Another evaluator suggested that some functions such as zoom should be relabeled to make them more intuitive.

3.4.2 Ruggedness

Evaluators were asked if the MSR components remained in place while the robot travelled over varying terrain: one agreed, two strongly agreed, and two did not respond. One evaluator noted that the robot travelled over two curbs, a grassy area and a bump without losing any MSR components. When asked if the system would be rugged enough for the evaluators’ use cases, two agreed, one was neutral and two did not respond. One evaluator stated that the Velcro mount needs to be improved. During the low-light activity, another evaluator experienced the core module falling off due to vibration caused by turning the robot in a tight circle. The developer then relocated the core module to the robot arm, which the evaluator felt was not an ideal location.

3.4.3 Visual Discomfort

Out of four responding evaluators, two disagreed and two strongly agreed that the lenticular display was free from flicker and the image remained stable during the inspection tasks. Although one evaluator said that the image remained stable, he chose “disagree” due to the difficulty posed by the video lag.

Throughout the OFA activities, evaluators were asked if they experienced any visual discomfort while operating the system. Four of the evaluators did not experience any issues. One evaluator stated that prolonged use of the system did result in some eye strain and headache. He decided to limit his use of the 3D image to close-up work only, and reported that this approach seemed to resolve the issue.

3.4.4 Overall Performance

Evaluators were asked if using the MSR system improved their ability to perform the tasks represented in the OFA scenarios; two disagreed, two strongly agreed, and one did not respond. One evaluator who disagreed noted that the video lag caused by the loss of communication between the OCS and the core module made him not trust what he was seeing on the lenticular screen. When asked if the stereoscopic view provided by the MSR is an improvement over the standard robot camera view, all five evaluators strongly agreed. One evaluated stated that as long as the video feed was not lagging, the view from the MSR was vastly superior when compared to the robot’s own camera.

Evaluators were asked if the MSR would be beneficial to them while performing their work duties. All four evaluators that responded strongly agreed. Two evaluators added the caveat that the video lagging issue would have to be fixed first. When asked if their agency would benefit from acquiring the MSR, two agreed and two strongly agreed.

Given the opportunity to say what they liked the most about the MSR, all five evaluators mentioned the clarity and quality of the video image in their responses. One evaluator also cited the ease of installation, while another mentioned the improved depth perception.

A different evaluator pointed to the improved lighting and camera zoom feature, and also stated that the 3D image would be useful for detail work.

Evaluators were also asked what they liked least about the MSR. All five evaluators mentioned the video lagging and/or signal loss issues they experienced. One evaluator added that there were too many wires connecting the camera to the core module, that the setup time would be too long in some scenarios, and that the Velcro mounting method is not a long-term solution. Another evaluator also commented the Velcro mount needed to be improved.

3.4.5 Potential Use Cases

Throughout the OFA, evaluators considered and discussed their potential uses for the MSR. One evaluator said he would use the MSR for situations requiring detailed work but may not take the time to set it up a quickly evolving situation (e.g., a hostage crisis) when getting a quick view of the situation would be the priority. Multiple evaluators said they would not use the stereoscopic image for driving the robot but rather for fine manipulation tasks where depth perception is useful (e.g., manipulating doorknobs to open doors, cutting open or unzipping bags, placing disruptors). Evaluators noted that even though the MSR camera could provide the necessary fidelity, they generally would not use a robot to cut wires or pull detonators from an explosive device.

3.4.6 Opportunities for Improvement

Evaluators also made suggestions for improvements to the MSR:

- Improve wireless transmission capabilities to eliminate lag and ensure the camera system works everywhere that the robot works.
- Improve component mounting options. Evaluators liked that the MSR could be retrofit on to a department’s existing robot, but suggested that it would be helpful to have custom mountings available so that components could more easily be fitted to the robot. One evaluator suggested that the ideal configuration for the MSR would be for the camera module to be added as a plug-and-play accessory to the robot that transmitted over the robot’s existing wireless system.
- Improve MSR cable management. During the OFA, some evaluators had difficulty with the cables between the MSR camera head and core module. They noted such cables could snag, be pinched, limit the motion of the robot arm or joints, or pull the camera out of alignment. One evaluator suggested integrating the core and camera components to eliminate cabling.
- Optimize the size of the MSR. Some evaluators suggested that making the batteries and components smaller would improve the ease of mounting components.
- Incorporate measurement scaling or range finding in the display. These would be useful for determining the size of objects in view and determining distance. Some robot tools (e.g., disrupters, lasers) are designed to operate best at specific distances from the object of interest.

4.0 CONCLUSIONS

The objective of the OFA was to assess the operational suitability of the MSR for bomb technicians. Five bomb tech evaluators provided feedback on the installation, imaging capabilities, communications range and general usability of the system. Throughout the OFA, evaluators suggested opportunities for improvements to make the MSR more suitable for use in the field.

MSRs were installed on each of three different bomb robots: the Telemax Hybrid and ICOR models T5 and MK3. The MSR camera heads were attached to each robot arm using Velcro and a ball joint; the core module's mounting location varied by robot. System setup ranged from about 10 minutes up to 30 minutes as evaluators and technology developers experimented with getting the right attachment location and method on robots that they had not previously used with the MSR. Evaluators had mixed feedback on MSR installation and on components shifting or detaching during operations. For the Telemax Hybrid, the MSR's video/data cable between the camera head (installed at the gripper) and the core module (installed on the robot body) got wrapped around the arm a few times because the arm had the ability to fully swivel. This movement caused the wire to wrap around the robot arm and pull the camera head off its Velcro mounting. Evaluators noted that MSR mounting strategies should be improved. They also suggested developing custom mounting brackets for each type of robot rather than using Velcro and zip ties.

Evaluators were readily able to use the MSR and orient their head position to view the stereoscopic image. Although one evaluator had minor visual discomfort viewing the stereoscopic image, the reviews of the MSR camera and display were positive. Evaluators stated that the quality of the MSR camera's image was excellent and superior to the robots' onboard cameras. They considered the depth perception afforded by the stereoscopic view helpful. They believe that using the MSR would improve their ability to see small details and perform tasks that require fine manipulation or depth perception. Evaluators noted some difficulty with viewing the screen in bright daylight conditions but felt the difficulty could be overcome by moving the operator control station inside a vehicle.

Throughout the assessment, the video image from the MSR lagged behind that of the robot's own camera. The lag increased (up to 20 seconds) with increased distance between the robot and operator control station. The signal was lost when the robot moved beyond approximately 150 to 250 feet from the control station and when the robot went into or behind a concrete block building. This limitation prevented evaluators from accomplishing some of the planned activities. Evaluators remarked that the transmission problems must be fixed so that the camera transmission works everywhere the robot works.

Overall, evaluators considered the MSR image quality and depth perception to be improvements over existing systems, but emphasized that the wireless transmission difficulties must be fixed for the technology to be viable. Evaluators suggested enhancements in component size, mounting method, cable management and distance/measurement capabilities to further improve the technology.

5.0 APPENDIX

Table 5-1 summarizes the results of the evaluator questionnaires across all criteria. The number in brackets after the criterion description represents which requirement number from Table 1-2 the statement addresses. The number in each response column from Strongly Agree to Strongly Disagree represents the number of evaluators who selected that response for each criterion. Because not all evaluators were able to complete some activities, the number of responses per criterion varies.

Table 5-1 Evaluation Criteria and Evaluator Responses

Criterion	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Installation					
Setup of the Operator Control Station was quick and straightforward. [1]			2	2	1
Installation of the camera and core components onto the robot was quick and straightforward. [1]			1	2	2
No modification to the robot was necessary when installing the system components. [2]			1	3	1
The design of the installed components would allow them to be installed on other types of robots. [3]				5	
After installation, the pose of the cameras was adjustable. [4]		1		2	2
The installation did not block the view of any of the robot's cameras. [5]				3	2
The installation did not impede any of the robot's movement capability (e.g., movement of robotic arm) or potential uses (e.g., components did not extend beyond the robot's body such that they would impede robot operation in narrow aisles or pathways). [5]		3			2
Camera and Display					
The field of view provided by the MSR is sufficient. [6]				3	2
The monocular view of the MSR is an improvement over the existing robot camera. [7]				2	1
The camera zoom feature was sufficient for my use. [7]				3	
The lenticular display presented object colors accurately. [8] DAYLIGHT OPERATION				2	3
The lenticular display presented object colors accurately. [8] LOW-LIGHT OPERATION				2	1

Criterion	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
The stereoscopic image from the lenticular display was free from distortion and presented object shapes and forms accurately. [9] DAYLIGHT			1*	2	2
The stereoscopic image from the lenticular display was free from distortion and presented object shapes and forms accurately. [9] LOW-LIGHT				2	1
The display image was accurate enough to allow reading of small print during the inspection task. [9] DAYLIGHT			1*	2	2
The display image was accurate enough to allow reading of small print during the inspection task. [9] LOW-LIGHT				2	
The depth perception provided by the stereoscopic image improved my ability to complete the task. [9] DAYLIGHT				2	3
The depth perception provided by the stereoscopic image improved my ability to complete the task. [9] LOW-LIGHT			1*	1	
The lenticular display was sufficiently bright to be viewable in direct sunlight. [10, 11]			2	2	1
Glare and lens flare from sunlight on the camera lens were not an issue during the task. [12]			1	2	2
The dimmable LED arrays provided sufficient light to perform the tasks. [12]				3	
Communications and Range					
There was no loss of communication or degradation of the display image during the inspection task at 500 ft line of sight from the OCS. [13]	1	2			
General					
Operating the MSR was intuitive. [14]				3	2
The installed components did not detach or shift while the robot travelled over varying terrain. [15]				1	2
The system would be rugged enough for my use cases. [15]			1	2	
The lenticular display was free from flicker and the image remained stable throughout the inspection task. [16]		2			2
Use of the lenticular display did not cause any discomfort (e.g., eye strain, headaches, difficulty maintaining head position). [16] DAYLIGHT				2	2
Use of the lenticular display did not cause any discomfort (e.g., eye strain, headaches, difficulty maintaining head position). [16] LOW-LIGHT		1		1	

Criterion	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Use of the lenticular display did not cause any discomfort (e.g., eye strain, headaches, difficulty maintaining head position). [16] GENERAL			1	2	2
Use of the MSR improved my ability to perform the tasks. [17]		2			2
The stereoscopic view provided by the MSR is an improvement over the standard robot camera view. [17]					5
The MSR would be beneficial to me while performing my work duties. [17]					4
My agency would benefit from acquiring the MSR. [17]				2	2
* Respondent indicated that this neutral rating was based on not being able to adequately assess the criterion during the activity.					

6.0 REFERENCES

[1] Science & Technology Directorate, Department of Homeland Security, "Statement of Work for Robotic Stereoscopic System," 2020.

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[3] International Electrotechnical Commission, "Information technology — Coding of audio-visual objects — Part 10: Advanced video coding. ISO/IEC 14496-10:2020," 2020.

[4] Science & Technology Directorate, Department of Homeland Security, "Robotic Modular Stereoscopic Retrofit System Operational Field Assessment Plan," 2021.

[5] W. C. Stone, "NIST Construction Automation Program Report No. 3 Electromagnetic Signal Attenuation," National Institute of Standards and Technology, Gaithersburg, Maryland, 1997.