# Human-System Interaction for Bomb Squad Applications: Preliminary Experiments with Low Cost Cameras in Real World Deployment.*

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***Abstract*— A sufficient level of situational awareness is crucial in the operation of remote, teleoperated robots to fulfil a mission. While much work has been done in user interfaces, camera systems and so-on to improve situational awareness, it is an unfortunate fact that few of these developments have filtered down into operational use. In this paper, we describe our preliminary work on improving situational awareness provided to the operator of a tEODor Explosive Ordnance Disposal Robot. We focus on the effect of adding low cost wide angle cameras to an existing, deployed robotic platform and the result of experiments as to effective placement of the cameras within the existing robot system. Unique to our work is the fact that these improvements have been used operationally and found to improve mission performance.**

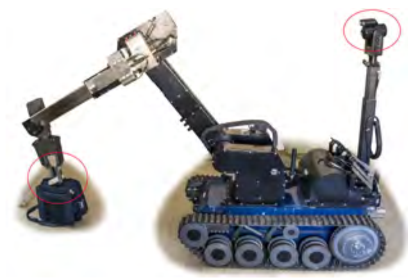

Fig. 1. The tEODor robot. This work focuses on adding cameras to the existing camera mast and gripper (both circled).

## I. INTRODUCTION

The field of human-system (or human-robot) interaction, as applied to response robots, has been the subject of much research [1], [2], [3]. In this context, we consider the interaction between the robot operator and the robot; the robot itself is not interacting with anyone downrange. A crucial aspect of this interaction is the situational awareness that the robot provides to the operator. In some cases, this is the purpose of the mission – that of observation. In other cases, situational awareness is required to guide the operator's use of the robot in remotely interacting with the environment, be it to travel through and over the environment, and to interact with and manipulate the environment.

Many research solutions to improve situational awareness have been proposed. These include improvements in camera selection and placement, additional sensors such as bumpers, laser, ultrasound and radar, and advanced methods of presenting this to the operator including visual displays, audio and tactile feedback [4], [5], [6]. While many studies have been performed in simulation and in training exercises, few have transitioned into operational deployment. The barriers of unfamiliarity, cost, inertia of deployed equipment, risk adversity, compliance have resulted in a situation where responders have yet to benefit from these improvements.

In this paper, we describe preliminary work in using low cost, off-the-shelf wide angle cameras as a low cost, high impact addition for improving the situational awareness of response robots, in a manner that is conducive to short term operational deployment. One feature of this work is that we augment the capabilities of an existing robot, holding other factors such as the robot's geometry, control unit and operator constant.

The second author, who performed much of the work on sensor placement, is an experienced EOD robot operator who has worked operationally with the tEODor robot for the past 5 years. As a close collaboration between researchers and responders, this work is also unique in its focus on the application, with developments that are likely to be readily accepted by the responder community.

We also present very preliminary analysis of the use of these improvements. This includes training scenarios and, uniquely, real world deployment. Despite being preliminary, the results that this work presents are significant not only in confirming operationally what has been hypothesised in the lab, but also in demonstrating how even a very low cost, low risk set of modifications can vastly improve mission performance now. In the process, it demonstrates how active collaboration between responders and researchers can accelerate the deployment of technologies that improve these crucial capabilities.

## II. THE ROBOT AND APPLICATION

In this paper, we describe modifications made to the Cobham Mission Equipment - Unmanned Systems (formerly Telerob) tEODor Explosive Ordnance Disposal (EOD) robot, shown in Figure 1. This robot design has been in active deployment across Europe and Asia for over a decade.

The tEODor is a fairly large robot, by human-scale standards, with a length, width and height of 1,300 mm, 685 mm and 1,240 mm respectively and an unladen weight of 375 kg. It has a payload of up to 100 kg within 400 mm of the front of the robot. The tEODor is often deployed in situations where it is necessary to manipulate heavy objects, even where its size is less than ideal. Examples include opening

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doors or clearing debris to gain entry for reconnaissance, and carrying disruptors or tools, where it is necessary to survive a significant recoil or apply a significant force.

The tEODor has up to two pan-tilt-zoom cameras, one mounted on the elbow of the arm and one on an optional extending mast at the rear. There is also a low driving camera and rear view camera mounted to the turret and a camera mounted to the gripper. An aiming camera can optionally be mounted to the disruptor. Examples of the vision afforded to the operator by these stock cameras is shown in Figure 6. The situational awareness afforded by the tEODor is typical of that provided by deployed robots of its size.

For the purpose of this discussion, we will divide some of the more challenging operational tasks of EOD robots into four categories, each with different requirements for situational awareness. This list is not intended to be exhaustive, rather it is intended to illustrate some of the salient challenges for which EOD robots are operationally useful.

- Driving of the robot through an environment, possibly with rough terrain and/or confined spaces.
- Manipulation of objects in confined space, such as removing obstructions, opening doors and picking up objects where the robot's movement is restricted.
- Manipulation of objects in clear space, such as a suspicious package in an otherwise open environment.
- Inspection of confined voids such as under and inside vehicles.

We define confined space to be spaces that are sufficiently small so as to restrict the robot's opportunities of movement. Examples include narrow doorways, passageways and cluttered environments. Based on our prior work [1], [7], we identified surrounding-area situational awareness as a clear deficiency in operating robots such as tEODor to perform tasks in these categories.

### A. *Driving through an Environment*

The "drinking straw" view afforded by the current cameras' optics means that the operator cannot see the entire robot, within its environment. Instead, the operator needs to cycle through the various cameras and, using their understanding of the environment and the robot's shape, imagine where unseen parts of the robot are relative to environmental features. In an operational setting, this is problematic.

Figure 2 represents a typical case. The operator failed to detect that a tool mounted to the robot had hit a doorknob when passing through a door, causing the door to jam. While the operator had seen both the tool and doorknob previously, they were no longer visible in the camera view at the time. In other exercises, robots have been caught in overhead obstacles or leaning debris. These issues have led to a reluctance to use robots such as tEODor in confined spaces or unstable structures, where they are most useful, due to a fear of causing secondary collapse.

### B. *Manipulation in Confined Space*

Manipulation in confined space requires the robot to push, pull, grab or otherwise move objects in the environment in a location relative to the robot that is not of the operator's choosing. There is little opportunity for the robot to move in order to facilitate easier manipulation. Examples include opening doors, removing debris from a narrow path or picking up an object from a cluttered environment.

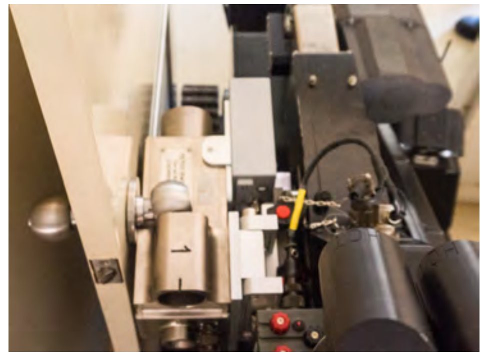

Fig. 2. The robot colliding with a doorknob while attempting to traverse through a door. The operator drove by looking through a camera that could not observe the position of the doorknob. The only camera on the stock robot capable of observing the doorknob (visible in the lower right of this image) did not provide a view suitable for driving the robot. This is a typical situation that could be avoided with improved situational awareness that would provide the operator with a more complete view of the environment.

Again, the narrow field of view afforded by the vast majority of deployed robots results in situational awareness problems. The operator only has a live view of the manipulator and not the rest of the robot. During our work on robot evaluations, it was not uncommon for the operator to move the robot, in order to pass through a door or to facilitate better manipulation, and collide with objects that had been observed in the past but that the operator had either forgotten about or did not fully understand the position of.

### C. *Manipulation in Clear Space*

A given manipulation task is typically easier in a clear or partially clear space, where the operator is free to move the robot. An example is a suspicious package left in front of an airport check-in counter. Being free to move also brings with it challenges of situational awareness as the operator must stay aware of the robot's surroundings. It is all too easy for the operator, concentrating on the task at hand and assuming that they are free to move, to move the robot around and collide with the object being manipulated or with the few obstacles that may be present in the space.

Traditional narrow angle cameras again tend to require the operator to regularly direct perception from the task to the wider environment to perform these motions, again risking either missing something in the environment or losing grip of what they are manipulating. A wide angle view that allows the operator to observe and monitor both in context should reduce risk of collisions and manipulation errors while increasing efficiency by eliminating the need to switch cameras or move pan-tilt-zoom units.

### D. Inspection of Confined Voids

Confined voids are those with openings that are too small for the robot to drive into and difficult or impossible to insert its normal arm. Examples include the spaces under vehicles or inside vehicles where access is gained by breaking a window or drilling a hole. Typically, such inspection is performed by probing – the insertion of a camera on an arm, be it the robot's normal manipulator or a camera on a dedicated probe that is held in or attached to the robot's normal manipulator. Two tasks in the inspection of confined voids require elevated situational awareness.

The first task is that of inserting the camera into the void space, ensuring that it does not adversely interact with the environment or the edges of the access hole. For larger robots such as the tEODor, this task tends to be satisfied to a reasonable extent by the existing cameras on the robot. Its size allows the existing pan-tilt-zoom mast camera to be placed a sufficient distance from the end effector to observe the entire workspace, notwithstanding issues highlighted in Sections II-B and II-C.

The second task is performing the actual inspection. The stock tEODor is poorly suited for such inspection tasks because the gripper, on which the manipulator camera is attached, is very large (see Figure 4) and the camera is narrow in angle. This makes it very difficult to perform a complete inspection. It is possible to fit an endoscopic camera to the gripper on the tEODor, this can be inserted into the void and steered remotely. However, this solution is expensive and relatively fragile. It also takes up one of the pan-tilt-zoom camera ports on the robot (typically the pan-tilt-zoom mast camera).

## III. Related Work

The topic of Human-System Interaction (HSI), sometimes also referred to as Human-Robot Interaction (HRI) has been studied for a long time. In the context of this work, we restrict ourselves to a discussion on HSI from the perspective of a human gathering information and projecting their intent through the robot. Although also considered part of HSI, we do not consider the case of the robot itself interacting with a human who may be downrange or any other cases where a human may interact with the system.

The concept of investigating camera placement for the aforementioned tasks is hardly new. For example, the RoboCupRescue Robot League competition [7] has seen robots with a wide variety of solutions to the problem of situational awareness for many years [6]. The benefits of a high overhead view in particular, have been well documented, including the first author's past work [1].

However, it seems that very few operational robots have taken advantage of these advancements. Most larger robots have cameras on masts while even some mid-sized robots, like the Packbot EOD, have cameras that can be placed at a significant height. However, most of these cameras seem to only offer a restricted view of the robot. Wide angle optics, which allow the operator to clearly see the robot in the context of its surroundings, are virtually non-existent among widely deployed systems.

In the first author's experience during HSI-related testing, even these limited narrow-angle cameras are often not used. It is not uncommon for an experienced operator under test to attempt a HSI-related test such as the confined space slalom from the DHS-NIST-ASTM International Standard Test Methods for Response Robots suite [8], then perform significantly better on a second attempt once they are shown that driving through a raised camera, even if it's a camera on the gripper, can result in much better situational awareness.

To the authors' knowledge, documented testing of the effectiveness of these techniques, on the same robot with the same operators, using deployed systems within the standard test methods, does not exist.

There are fewer solutions to the issue of situational awareness in confined space voids. They include:

- Search cameras and hardened probes like the VIP Gander [9].
- Combined drilling and inspection tools such as the WM Robots Hazprobe [10].
- Variable geometry probes including industrial endoscopes and snake robots [11].

Search cameras and probes tend to be inflexible and unwieldy while models with small pan-tilt units behind the camera suffer from being delicate. Added flexibility, as appears in true snake robots attached to end effectors, further increases complexity and the risk of damage. All of these solutions also tend to be expensive and limited in availability, further reducing their utility by reducing the willingness of responders to deploy them.

## IV. Modifications to the Robot

Unlike much of the prior work in this area, including the prior work of the first author, we restricted our modifications to those that were operationally practical. Any modifications should:

- Measurably improve situational awareness.
- Minimally degrade existing capabilities.
- Not require permanent modifications to the robot.
- Be relatively low in cost (less than $1,000).
- Utilise existing radios and operator control unit (OCU).
- Not require additional calibration or other steps immediately prior to or during deployment.
- Require minimal to no re-training of operators.
- Maintain the robustness of the robot system, including weatherproofing.

It was hypothesised that the addition of low cost, readily available wide angle cameras, often sold as car reversing cameras, could improve situational awareness and corresponding mission effectiveness while satisfying these criteria.

Two wide angle (120°) fisheye car reversing cameras (non-mirrored) were added to the robot and connected to auxiliary power and analogue composite video connectors on the tEODor robot[1]. Video was transmitted through the

[1]The authors gratefully acknowledge the assistance of Cobham Mission Equipment - Unmanned Systems for their assistance.

Fig. 3. The wide angle camera attached to the back of one of the existing pan-tilt-zoom cameras.

Fig. 4. Flexible probe consisting of a wide angle camera and LED lamp attached to the back of the tEODor's gripper. This allows the gripper to be used as normal, such as to hold and use a drill (left) and then turned around to deploy the probe (right).

robot's normal video transmission system and viewed by the operator using the normal operator console.

The first camera was placed at the rear of one of the pan-tilt-zoom cameras as shown in Figure 3. By turning the pan-tilt-zoom camera 180°, the operator will have a view of the entire robot in one frame while maintaining the ability to point the camera. The second camera was placed at the end of a flexible probe, in front of an LED lamp. The probe was attached to the back of the gripper. The gripper on tEODor is able to rotate backwards 180°, allowing the probe to be inserted into voids, under vehicles and so-on. This also allows tEODor to drill a hole using a drill mounted in its gripper, rotate the gripper 180° and then insert the probe into the hole as shown in Figure 4. This probe could be considered to be a lower cost, simpler and more robust, albeit larger, version of an endoscopic camera. Both cameras were automotive grade so were intrinsically weatherproof. Their small size, combined with their mountings, resulted in a system that was deemed sufficiently robust for deployment.

Cameras with fisheye lenses, as distinct from rectilinear lenses, were deliberately chosen for this application. A rectilinear lens is designed so that straight lines in the scene appear straight in the image. In contrast, a fisheye lens will cause straight lines in the scene to bow out from the centre of the image. In many applications, this is an undesirable effect. For the purpose of situational awareness, however, fisheye lenses exhibit two important benefits. Fisheye lenses can be made wider angle than rectilinear lenses, at least at a low size and cost. Fisheye lenses also exhibit a natural foveation – where the centre of the image has a higher level of acuity (ability to resolve small objects) as compared to the edges, just as the human eye does. Such a phenomena is useful in allowing the operator to maintain situational awareness at the edges while also enabling detailed inspection of objects at the centre.

## V. RESULTS

As touched on briefly above, this work is unique in two aspects. It makes use of the one robot, with and without the addition of the wide angle cameras, allowing all other variables to be held constant. It also makes use of equipment already in operational use, with experienced, professional responders at the controls. This ensures that the results are an accurate reflection of what is operationally capable in the immediate term.

This work is still preliminary and more formal, quantitative testing of the effects of the modifications on situational awareness, consistent with the DHS-NIST-ASTM International Standard Test Methods for Response Robots [12] is forthcoming. In the meantime, preliminary experiments have been performed both in realistic training scenarios as well as in operation. Three scenarios were particularly salient, two in training and one on a real operation where there was significant risk to life and property.

### *A. Clearing a Void Space*

The first scenario was a training exercise involving the inspection of the locked trunk of a vehicle, as part of clearing a vehicle suspected of harbouring an explosive device. Standard practice to inspect a void involves drilling a hole, stowing the drill and then grasping and inserting an endoscopic search camera. While the tip of the search camera can be bent remotely, allowing the camera to be steered, its relatively narrow field of view requires the operator to scan the environment. Disorientation is a significant risk due to the inability to see multiple landmarks at once.

The wide angle probe camera, mounted on the rear of the gripper, alleviated the need to change tools downrange when switching from drilling to inspection. Its wider angle also allowed more of the trunk to be viewed at once without needing to move the camera. Although the probe has no actuation, it was discovered that pushing the probe against

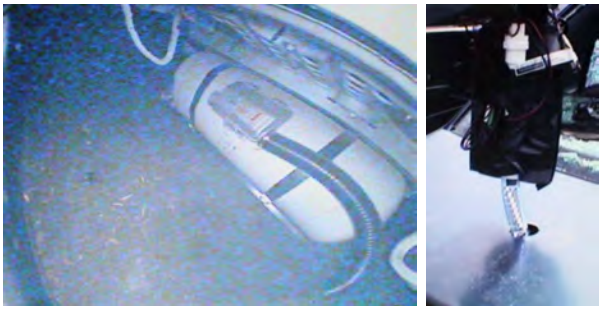

Fig. 5. The view from inside the trunk (left). The probe can be steered effectively by pushing against the edges of the hole, as observed from the pan-tilt-zoom camera on the robot's elbow (right). These can be merged into a picture-in-picture view that allows the operator to view the vision from the probe camera while also keeping watch of the surroundings.

the edges of the hole allowed the camera to be pointed sufficiently to inspect the entire trunk as shown in Figure 5. Although the wide angle lens affords reduced acuity as compared to the narrower angle endoscopic camera, its central acuity was sufficient for this purpose.

### B. Navigating a Cluttered Environment

The second scenario was also a training exercise involving navigating a cluttered technical workshop. This preliminary exercise is a precursor to formal, recorded testing in the DHS-NIST-ASTM International Standard Test Methods for Response Robots. This exercise served to both familiarise the responders with the wide angle camera and to provide an opportunity to experiment with different ways of mounting the camera so as to best improve situational awareness.

Operators were tasked with circumnavigating the room without colliding with obstacles including desks, chairs and irregular structures. Each operator performed this test remotely, once with only the standard cameras on board the robot and once using the additional wide angle camera mounted to the back of the pan-tilt-zoom camera.

A typical situation encountered during this exercise is shown in Figure 6 where the robot had to be driven through a narrow space. In this example, with only the conventional cameras, the operator had to continuously scan around the robot, checking the four corners as well as protruding parts of the arm for possible collisions. This is a lengthy process and requires the operator to memorise and predict the positions of objects relative to the robot.

With the addition of the wide angle camera view, it became possible for the operator to simultaneously monitor three of the four corners of the robot. Although the rear left corner was blocked by the camera's mounting, it was still possible to check for objects that came close to this area. Alleviating the need to continuously move the camera resulted in a significant increase in speed. Presenting the robot's situation relative to its environment in a complete view also reduced errors associated with the operator forming an incorrect or incomplete model of the robot's situation.

For example, to continue at this point it was necessary for the robot to move forward and to the left. This required monitoring the rear right corner of the robot to ensure that it did not hit the workbench as it swung to the right while also monitoring the chair to the left to ensure that it would not be disturbed.

Fig. 6. The tEODor robot navigating a particularly tight environment, in this case a gap with approximately 3 cm of clearance to either side of the robot. The views from the standard cameras are shown left top and centre. The view from the wide angle camera is shown to the bottom left.

As this preliminary exercise also served as an opportunity to experiment with different camera placements, accurate data regarding improvements in performance was not gathered beyond qualitative observations of fewer collisions, vastly improved speed and reduced operator stress. Formal testing is the subject of current work.

### C. Inspecting an Unstable, Confined Space

The third scenario was during an active deployment in response to an explosion at a public building. The front of the building was extensively damaged as shown in Figure 7. It was necessary to inspect the inside of the building to determine the extent of damage and identify hazards. These included risks of further explosions, secondary collapses and exposed wiring due to the partially collapsed ceiling. This required entering the damaged front of the building, negotiating rubble and moving through a doorway that was partially obstructed from above and to the side as shown in Figure 7. It was also necessary for the robot to move some of the partially collapsed structure to render the area safe for human responders to enter.

Ordinarily, the responders would not have used the tEODor robot to address this situation. Its size and limited situational awareness made the risk of inadvertent collision with the damaged structure, and possible uncontrolled secondary collapse, too great.

With the added wide angle camera, it became possible for the operator to guide the tEODor robot through the confined spaces in order to perform the inspection task. Particularly important was the ability to keep watch on the debris on both

Fig. 7. The damaged front of the building that the robot needed to enter (left). In addition to clearing or stabilising this debris, the robot also needed to negotiate a doorway that was partially obstructed with low hanging obstacles (right). This view from the wide angle camera mounted to the robot's existing pan-tilt-zoom camera affords a view of the robot, in context among these obstacles, something that would require lengthy continuous scanning with a traditional narrow angle camera. Note that the left and right edges have been substantially cropped for reasons of operational sensitivity; the lower left frame of Figure 6 is representative of the field of view of this camera.

sides of the robot as well as overhead. Due to the highly unstructured nature of the environment, it was necessary to continue monitoring these areas to ensure that the robot would not become trapped. It was also necessary to detect if there was any unexpected motion that may signal further instability.

## VI. CONCLUSION

In this paper, we have described our preliminary efforts in extending our past work on ways of improving situational awareness of response robots. The focus of this new work is on augmenting existing, deployed robots with low cost, wide angle cameras in a way that can be used operationally. Although statistically significant, quantitative testing using the DHS-NIST-ASTM International Standard Test Methods for Response Robots is forthcoming, preliminary missions, both in training and deployment, have already demonstrated how these additions have improved the ability to carry out operational missions.

The next steps involve further experimentation to determine the optimal placement of these cameras, including the use of additional probes and mounts. Work has already begun on a new probe, shown in Figure 8. This is compatible with the robot's tool changing mechanism and has with two cameras that afford both an end and a side view, reducing the need to bend the probe.

This will be followed by testing of the ability of the operator to perform various test methods, relevant to the challenges outlined in Section II, with and without the additional cameras. These include:

- Confined Space Obstacles: Doors
- Confined Space Obstacles: Decreasing Slalom

Fig. 8. The new camera probe, compatible with the tEODor's tool changing mechanism and housing two cameras, one pointing out of the end and one pointing sideways.

- Human-System Interaction: Confined Space Maze
- Manipulation: Dexterous Manipulation: Cab & Cargo Bay
- Manipulation: Dexterous Inspection: Cab & Cargo Bay

Beyond these tests, further work will include augmenting other robots with similar wide angle cameras and measuring the change in performance in these tests. It is anticipated that similar improvements in situational awareness will translate into similar improvements in the ability to carry out missions. The ultimate goal is to raise awareness among both the responder and manufacturer communities as to the need for wide angle cameras and other simple features that can improve situational awareness.

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