Autonomous Robots in SWAT Applications: Research, Design, and Operations Challenges

Mr. Henry L Jones
Prof. Stephen Rock
Aerospace Robotics Laboratory
Stanford University
(650) 723-3389
hlj/rock@arl.stanford.edu
http://arl.stanford.edu

Lt. Dennis Burns
Palo Alto Police Department
Palo Alto, CA
(650) 329-2406
pd@city.palo-alto.ca.us
http://www.papd.org

Dr. Steve Morris
MLB Co.
Palo Alto, CA
(650) 424-9552
mlbco@mindspring.com
http://www.spyplanes.com

Abstract

This paper describes the efforts of Stanford University's Aerospace Robotics Laboratory (ARL), the Palo Alto – Mountain View (California) Regional Special Weapons and Tactics (SWAT) team, and the MLB Company to bridge the gap between the perception of potential uses of autonomous robots in police SWAT environments and the reality of their application. The ARL researchers were given freedom of movement throughout live SWAT field training exercises so that they could simultaneously monitor the command post actions, SWAT team movements, and suspects' activities. This perspective highlighted five significant challenges that should influence future work.

First, the considerable difficulty in building a consistent centralized world model indicates the necessity of relying on local sensing for robot tactical maneuvers. Second, the SWAT team referred to objects in the environment throughout their communications, yet the recognition and manipulation of previously unknown objects is a difficult task for robots. Third, the time available for tactical planning was observed to be one of two extremes: nearly infinite or infinitesimally small. Fourth, the SWAT environment has much uncertainty, and SWAT team members are reluctant to introduce any additional uncertainty, friendly or otherwise, via a robot. Finally, the operator plays important roles that must be supported by the robot and the user interface.

This paper describes in detail the SWAT exercises that were observed, the challenges indicated by these observations, and a demonstration of an autonomous robot – the MLB Bat unmanned aerial vehicle – in a SWAT environment.

Introduction

This paper describes the efforts of Stanford University's Aerospace Robotics Laboratory (ARL), the Palo Alto – Mountain View (California) County Special Weapons and Tactics (SWAT) team, and the MLB Company to bridge the gap between the perception of potential uses of autonomous robots in police SWAT environments and the reality of their application. The robot

builders (the ARL researchers and MLB designers) and the SWAT leaders felt that such an effort would address an area of limited current understanding.

Robotics motivation

Many field robot and autonomous vehicles builders envision their work as assisting humans in positive ways – particularly by replacing them in dangerous, dirty, or dull missions. However, the experience of these robot creators in such hazardous situations is usually limited. Thus, there is some uncertainty regarding what characteristics a robot needs to have to truly be effective in these missions. Some research topics are more on the critical path to deployment than others, and some design criteria should be weighted differently. This research sought to identify these important areas for future work.

SWAT motivation

SWAT team members recognize that they hold one of the most dangerous civilian occupations. They want to take all possible steps to minimize that danger while accomplishing their mission. From exposure to robotics through the popular media, they envision the possibilities that robots may have to make their jobs safer. However, they do not have a true picture of the actual strengths, weaknesses, or operations requirements of modern robots. SWAT leaders do not know how soon they might be able to involve robots in their operations and are unsure of robots' potential cost. They also have concerns about autonomous robot use in an environment that often leaves little margin for error.

Through the research efforts described in this paper, SWAT team leaders were educated in the realistic capabilities of current autonomous robots through discussions with the ARL and demonstrations by MLB. The SWAT members were shown the operations realities of autonomous robots and the ramifications of their deployment. At the same time, the Aerospace Robotics Laboratory and the MLB Company learned about working in a SWAT environment. In particular, some important qualities for a SWAT robot were identified. The broader purpose of this research was to produce this paper and educate the robotics community about SWAT applications as discovered through this unique partnership.

Outline

This paper will give a brief description of the SWAT environment and the methods of observation available to the ARL researchers. The observations themselves are then discussed and are followed by the research and design challenges that were identified. Next, the use of the MLB Bat autonomous airplane in a SWAT exercise is discussed as well as the operations challenges that were highlighted through this preliminary test.

Background and Terminology

The audience for this paper is expected to be primarily from the robotics and automated vehicle fields and inexperienced in SWAT operations and terminology. Consequently, a description of SWAT teams and the SWAT incident environment will be given. The reader is assumed to have a basic understanding of robotics.

Police Special Weapons and Tactics teams

Police SWAT teams are responsible for handling high-risk tactical situations involving barricaded suspects, hostage situations, and the serving of warrants. The primary goal of the team is the successful conclusion of high-risk situations through the use of specially equipped and highly trained personnel without injury or loss of life to citizens, suspects, or police officers. Officers assigned to the SWAT team are required to pass a physical agility and strength test and a psychological examination, and to participate in monthly SWAT-specific training sessions.

Components of a SWAT team deployed at a site vary from incident to incident, but typically include a command structure, tactical teams, a Hostage Negotiation Team (HNT), and a sniper component. The command structure consists of an incident commander, the tactical commander, and the Hostage Negotiator Team leader. These individuals establish an incident command post at some distance from the suspect. The location containing the suspects, hostages, and focus of the action is known as the objective site. The command post is located at a distance close enough to enable speedy travel by foot to the objective site, but far enough away to provide a safe and secure location for the command structure to function. A generic incident site map is shown in Figure 1.

The incident commander ultimately makes the critical decisions and is responsible for the incident as a whole, including interactions with the press, coordination of action between the various team components, and handling logistics. The Hostage Negotiator Team works to achieve peaceful resolution of the incident through a dialogue with the suspects, and its leader is responsible for communicating the status and progress of the HNT to the other commanders and guiding HNT activities to complement the tactical squads.

The tactical commander's role is to coordinate the activities of the tactical teams – assault group, rescue element, sniper component, and perimeter control – throughout the incident. Typically, there is significant physical distance between the tactical commander (at the incident command post) and the tactical teams (at the action), and the commander does not have direct sight of the squads or the incident site. The tactical commander thus relies on radio (voice only) technology to gather

information from and convey commands to the tactical teams. In some cases, members of the tactical squads will return to the command post for face-to-face meetings with the tactical commander.

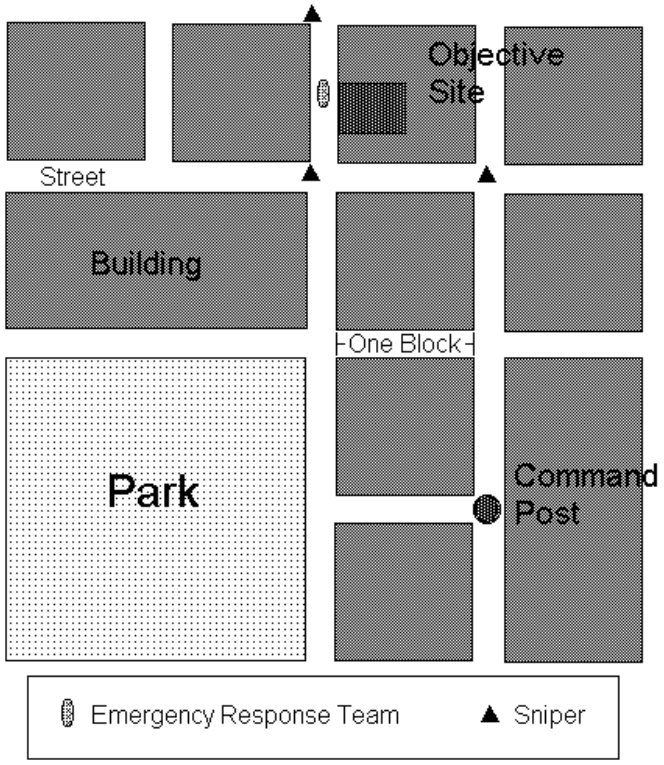

Figure 1 - Generic SWAT incident site layout

Also at the command post are tactical dispatchers, who handle most of the communications to the external world and from the commanders to the deployed squads. The dispatchers also maintain logs of all activities, descriptions of suspects and hostages, and maps of the objective site. This information is posted for display to the command structure and is used for tactical decisions.

Hardcopy city planning maps are kept in each patrol car, so a detailed map of the neighborhood – street locations and widths, buildings, open lots, and routes of access – is immediately available to the SWAT team. Other information derived from intelligence sources (e.g. government records, neighbors, building supervisors), such as auxiliary maps and building layout descriptions, may be photocopied and distributed to the appropriate team members.

SWAT conduct at the incident site

The tactical commander provides instruction to the tactical squad leaders within minutes of arrival. One squad is the Emergency Response Team, which is immediately given contingency plans and sent to the objective site. A team of scouts is then sent to create an assessment of the situation and provide prospects for entry methods, methods of safe approach, and descriptions of other salient features. Snipers are also put in place to gather intelligence and report to the command post. These

units would normally be outfitted with advanced optics, such as scoped rifles or high-powered binoculars.

Then, while the team waits for the Hostage Negotiator Team to achieve a peaceful resolution of the situation, the tactical commander and the tactical squads devise an assault plan. When the scouts return, they are integrated back into the tactical squads. The team draws maps on paper and in chalk on the street, and practices the movements and timing that will be used in the assault. This is an unrushed process, and the tactical team will make the rest of the team wait, if possible, until they are satisfied with their plans.

After the plan is set, the tactical squads deploy as appropriate. The pace of operations is typically unhurried and deliberate. Position reports are initially provided about once every two or three minutes, then slow down as squads settle into their positions. Twenty minutes might pass between orders, although this depends significantly on the pace of the incident. Intentions of tactical squads are reported more frequently, perhaps every ten minutes. For the most part, though, the radio traffic is not particularly active.

Eventually, either the HNT is able to resolve the conflict peacefully or the assault teams are required. The coordination of the assault with the other components of the SWAT team is done by the tactical commander after the command has been given by the incident commander. The assault typically takes only a few seconds, and action is only sparsely reported to the command post. Ultimately, the squad leaders report the status of the suspect, the hostages, and the team members and the incident is over.

Observation Methods

For SWAT field training exercises, the primary objective is to execute realistic but controlled scenarios that accurately model potential incidents. The location of the exercise is unknown beforehand to everyone but the exercise administrators. To avoid causing unnecessary alarm, the exercises are typically held in relatively remote commercial locations on weekend days, although residential areas are also used if sufficient notice can be given.

The SWAT team leaders gave permission to the ARL researchers to extensively study the field training exercises. The researchers were given vests to signal that they were observers in the exercise and thus were able to move freely throughout the incident area. This provided an opportunity to observe the evolving state of the exercise as well as view the events from various participants' perspectives. The researchers had complete access to all aspects of the exercise: the command post, the hostage negotiations, the sniper positions, the tactical squad movements, and the suspects' locations. The observation of field training exercises took place over four years.

Training exercises, rather than actual SWAT missions, were chosen for several reasons. First, great pains are taken in the SWAT exercises to replicate the events and activities likely to be encountered in an actual mission. Participants in the exercises are all active-duty officers who perform the roles they would in an actual mission and whose safety depends on their preparedness. Second, due to the high level of physical danger in most SWAT missions, the researchers would have had only limited access – certainly not the free movement enabled by the exercises. Finally, the objective was not to analyze team performance under the pressure of an actual mission, but to understand the SWAT environment. Training exercises, where instruction on proper actions is the primary objective, provided a natural mechanism for questions to be given and answered.

The researchers were also able to observe one actual SWAT incident, although with a much lower level of access. This incident validated the use of training exercises as an observation setting – the reduced access in an actual incident significantly decreased the amount of information available to observers, and the conduct of the team in an actual incident appeared to be identical to that of the training exercises.

To familiarize themselves with police and SWAT procedures before attending the exercises, the researchers participated in two regular patrol 'ride-alongs' with SWAT team members. Through informal discussion, the researchers learned the basic functions of the SWAT team, terminology, and other background information. The ride-alongs also provided time to convey the purpose of the study and to build the trust necessary to allow outside observers at a SWAT exercise.

Description of the exercises

Four exercises and one actual incident were observed over a period of four years: a combination residential/hospital hostage scenario, a workplace hostage scenario in a warehouse, two workplace hostage scenarios in an office building, and an actual residential hostage incident.

In the first exercise, a hostage situation started at a residence and then moved to a hospital clinic. The primary observation goal was to become familiar with SWAT operations. In the exercise, the SWAT team was called to a residential neighborhood where a hostage situation was underway. Upon arrival, an incident command post location was determined, neighbors described floor plans of the residence to the assault team leaders, and uniformed officers cordoned off the area. The SWAT tactical team spent over an hour developing an assault plan for the house. However, just before the assault was to begin, the exercise administrators revealed that the hostage and suspect had left the house before the SWAT team had arrived – according to the SWAT officers present, an example of the often-frustrating level of realism applied to these exercises. The hostage had been taken to a hospital

for treatment, and the suspect had taken additional hostages at the hospital clinic. The SWAT team moved immediately to the hospital site, redeployed its units, and the scenario continued.

A workplace hostage incident was the scenario for the second exercise, which was held at a warehouse for a school supplies company. The observers concentrated on the discrepancies between the command structure's perception of the situation and what was actually happening. The warehouse was surrounded by ditches, embankments, fences, and buildings that required extensive coordination among the snipers and the assault teams. The suspect barricaded himself in an office overlooking the main storeroom. Consequently, the assault team had to climb over and around large towers of boxes and other supplies that severely restricted their fields of view.

A workplace hostage situation was again the scenario for the third and fourth exercises, held at an abandoned office building. The fourth exercise went faster and smoother than the third, highlighting the effect of familiarity with an incident scene. The focus of these observations was the content and structure of communications to and from the tactical commander – to determine how he constructs his mental model of the action and examine the roles he plays coordinating the action from a distance.

In the actual SWAT incident that was observed, a distraught woman had barricaded herself in her bedroom. Officers at the scene had reason to suspect that she had her children and a gun with her. The possible combination of hostages and a firearm caused the incident to require SWAT intervention. The assault teams deployed throughout her house and were seconds away from acting when the suspect ended the incident peacefully.

Research and Design Challenges Identified

This research effort highlighted many challenges to be addressed in field robot research and design for SWAT environments, including:

- Reliance on centrally derived information may lead to significant problems.
- Objects in the environment should be basic building blocks of the robot operator for world model construction, plan building, and command.
- Time for robotic planning (path planning, task planning, and mission planning) during SWAT action is either extensive or nonexistent.
- Robot actions cannot increase the uncertainty for officers in the incident.
- The operator has significant and well-defined roles to play even if the robots are highly autonomous, and the robot and user interfaces must support these roles.

This research has led to a novel interaction design for the operation of multiple robots by a single operator that has been successfully used to command multiple heterogeneous robots.[1]

Each of the five main challenges will be discussed individually in the following sections, including examples from the SWAT exercise observations that highlighted these issues.

Developing global models

Many robotic systems take advantage of a priori information to provide accurate maps to the robot for navigation purposes. This seems to make sense, since in most cases robots operate in well-known environments. However, for SWAT applications, robot use cannot require accurate maps since they are often not available. Global information in general tends to be inferior to local information when available, particularly for the purposes of navigation and command and control.

For example, in the first exercise, the assault team was required to perform a blind assault onto the top floor from opposite sides of the hospital building. They would not be able to see the area they would assault until they charged through the staircase doors. They requested maps from the command post during their planning, and unfortunately the wrong map was provided. The incorrect map showed a hallway that passed around the outside of the floor, and the assault plans were made with this assumption in place. However, the floor actually had one hallway down the middle, which was discovered when the SWAT teams entered the doors and saw one another down the hallway. Great pains are normally taken to avoid this type of lethal crossfire situation. This highlights the requirement that any robot in a SWAT scenario utilize local information and not rely on a global source that may be incorrect.

Use of objects in the environment

The SWAT team communication content revealed that command dialogues often referred to physical objects in the environment. Objects provided ready points of reference to determine the location of the squads, describe the actions that could be taken, provide commands, and serve as common reference points for coordination between squads. For instance, in the following dialogue from the second exercise, each of these mechanisms can be seen.

Tactical Commander: W, do you have a visual on the suspect?

Officer W: No, (there is a) large stack of boxes between me and location (where I hear what) I believe is the suspect. [Object used to determine location]

TC: B, do you see a stack of boxes to your left in the direction of W?

Officer B: Affirmative.

TC: B, do you see a location for W to egress to that remains in cover? [Object used to coordinate action]

OB: Yes, there is a desk with a computer immediately to his left when he comes around the stack that he should be able to get to. [Object used to describe action that can be taken]

TC: Did you get that W? [Implied command using object]

OW: Affirmative – moving to the desk.

Such an emphasis on action in relation to objects in the environment is a particularly difficult challenge for robotics and is the subject of much research.[2,3] Action using well-known pre-defined objects is difficult enough, and the additional challenge of using unknown, unstructured objects creates significant research issues.[4] However, the frequency of references to objects by all members of the SWAT team highlight the importance of enabling objects as robot command tools.

Planning time

Robot planning systems often have time constraints or are judged by their speediness. The SWAT exercise observations showed that for SWAT operations, planning time effectively is either infinite while the SWAT team takes time to plan, or infinitesimal when actual action is taking place. For instance, before an assault, the assault and rescue teams will take as much time as necessary to develop and practice an effective plan. In some circumstances there is no hurry, as the Hostage Negotiator Team attempts to resolve the situation peacefully. Also, waiting for the suspect to become bored, tired, or in need of a break often plays into the hands of the SWAT team. In such a situation, a robot could be given a very large amount of time, at least on the order of tens of minutes, to plan.

On the other hand, when the assault team actually carries out the plan, the action takes place amazingly quickly. To the untrained observer, many of the movements seem to happen in the blink of an eye. There is basically no time to plan, as the officers are all reacting instinctively to the action. These instincts are the result of many hours of training. Robots that participate in this aspect of the SWAT operation must also have fast reactions or they would not be able to participate.

Uncertainty

Through interviews and informal conversations with SWAT leaders, and observations of the SWAT team in action, it is apparent that no technology will be tolerated at a SWAT incident that increases the level of uncertainty already present. Despite their willingness to put themselves into harm's way, SWAT team members are risk averse and take many steps to make their jobs as straightforward and safe as possible. There is already much uncertainty in many SWAT incidents that the team works to reduce, and a robot that behaves in an apparently unpredictable manner will not be accepted. Robot builders take caure that "intelligent" behavior is applied conservatively. Reactive, emergent, or learned techniques must have some constraints. Robots could simply shut down when

operational conditions exceed some limited bounds, so that the nearby SWAT officers know that the robot will effectively remove itself from unexpected situations.

Roles of the commander/operator

The roles played by the commander were cultivating common ground and coordinating action The commander is typically a long-time SWAT member who understands all the aspects of a SWAT deployment and consequently can form a quick mental picture from the information received by his tactical squads. By being detached from the squads and the danger of the objective site, the tactical commander can provide a clearer perspective and can integrate information from the other leaders at the command post. If one considers the SWAT tactical squad members as surrogate robots, and the tactical commander as their operator, it is apparent that even with highly autonomous robots, some human operator interaction is necessary.

When cultivating common ground, the commander uses objects in the environment to establish common points of reference for the actors. Current robot capabilities for perceiving objects are limited, and the operator should be able to supplement that perception. As coordinator of the action, the SWAT commander integrates external information into the conduct of the tactical squads. For instance, in every exercise the tactical team was required to perform actions according to the instruction of the HNT team. The HNT cannot realistically communicate directly with all the squad members, so the commander performs this function. Such external information should enter the plans of the robot via the operator in the same way.

Demonstration of an autonomous robot in a SWAT setting

To further refine the challenges and constraints presented by the SWAT environment, an autonomous airplane was demonstrated in a SWAT training exercise scenario. The demonstration was held during SWAT team training at the Military Operations in Urban Terrain (MOUT) facility at Fort Ord near Monterey, California. An autonomous Unmanned Aerial Vehicle (UAV), the MLB Bat, was used in the course of a field exercise to evaluate its potential use in an actual incident.

The MLB Bat

The MLB Bat is a complete UAV system that operates autonomously and delivers high quality video imagery and sensor data in real time. The 10 lb aircraft has a wing span of 60 inches but it folds into a 15 inch diameter tube that is 4 feet long. The compact ground station is transported in a small case so the entire system is man-portable. The aircraft can be prepared for flight within minutes and the mission course is specified by keying a series of waypoints into the ground station. Launch is by hand or from a catapult and an automatically deployed parachute is available for recovery. The Bat has a

flight duration of 1 hour and telemetry range of 2.0 miles and a payload capacity of 1 lb. The Bat has a guidance system that maintains position accuracy under autonomous control in calm conditions within 25ft of the specified course. Altitude is kept within 10 ft and airspeed within 5mph.[5] By flying below 500 feet above ground level, Bat flight is legal over most areas of the United States.

Figure 2 - MLB Bat & Ground Station at MOUT facility

Autonomous airplane demonstration

The Fort Ord MOUT facility is surrounded by considerable high terrain in close proximity to the site, and the weather on the demonstration day was clear but windy, with steady winds aloft of 15 to 20 miles per hour. This presented a challenge for the tasking of the autonomous airplane to ensure that terrain was avoided during takeoff, landing, and cruise.

In preparation for the flight, the SWAT leaders and an MLB operator agreed on an appropriate flight plan – a racetrack pattern that flew over the objective site on a long straight upwind leg. The MLB operator created the flight plan on the site while another MLB employee prepped the airplane and ground station. The setup took approximately twenty minutes.

In this exercise, the launch, operations, and recovery steps were all conducted at the same ground location. The SWAT leaders were able to move from their previous positions to the ground station location during the exercise. However, this is expected to be the exception rather than the rule, as discussed in a subsequent section. The MLB Bat and the ground station are shown in Figure 2 at the takeoff and landing site with the MOUT facility in the background.

During the flight, the SWAT leaders requested a faster revisit rate for the objective site. The MLB operator successfully retasked the UAV during its flight to shorten the length of the racetrack pattern by changing the waypoint locations. The UAV was in autonomous flight for over twenty minutes, and the flight ended when the SWAT leaders felt that they would not get any further benefit from additional aerial information.

The tactical commander directly observed the live video periodically, but it was rarely the focus of attention for very long. Two still pictures from the video taken are shown in Figures 3 and 4. The tactical commander did not interact with the control system directly, as this is inconsistent with his other interaction methods in the command post. However, since the airplane broadcasts the video, small receivers with monitors could be given to tactical squad members if deemed useful.

Figure 3 – Straight-down view of objective site

Operations Challenges Identified

The demonstration of an autonomous robot in a SWAT environment provided a better idea of how to utilize an autonomous robot and some additional important insights into the challenges that remain.

Potential uses

After observing the capability of the autonomous UAV, the SWAT leaders felt like the Bat would be useful as a SWAT scouting and intelligence-gathering platform. They were impressed by its small operational footprint and ease of use while in flight. Once the UAV is in place over the site, its main uses would be to provide frequent updates of the situation surrounding the site and to be tasked

specifically to obtain particular information before critical decisions are made. The SWAT leaders valued the ability to have direct input into the surveillance perspective and methods. The tactical commander is seen in Figure 5 reviewing flight video on a portable monitor after the airplane had landed, another valuable capability.

Figure 4 – Oblique view of objective site

For a planned incident, such as when a warrant is served, the UAV could be flown in advance to watch a house before the team arrives. This would let the observation of the objective site begin early and quietly, making it easier for the SWAT team to move comfortably without giving away the team's presence or cause the suspect to alter his behavior (e.g., run from the scene or destroy evidence). The SWAT leaders prefer to see the suspect without the suspect seeing them, and the Bat provided a real-time perspective that is much quieter and more discreet than a full-sized helicopter. SWAT teams rely on speed and surprise to reduce risk, and the UAV increases their capability to do so.

At an unplanned incident, no prior knowledge is available and the airplane could drastically reduce the scouting time, which currently takes up to 45 minutes. The UAV would be particularly useful if it could ultimately provide printed still photos of the site such as an overhead view of obstacles and side views of the entry and exit locations. The Bat was also considered valuable for floods, riots, event traffic, and other large-area reconnaissance needs.

Operational issues

Given the current scouting process, a 15-20 minute setup and deployment time would be an improvement, although faster would always be better. This SWAT demonstration pointed out that basic operator familiarity with the deployment surroundings and a streamlined vehicle and ground station shakedown process would be very helpful to increase the ease of deployment and decrease the time to get the UAV over the site. Information about terrain and other flight constraints (e.g., airspace and obstacles) would greatly assist the operator throughout the flight. GPS points for the incident site or georeferenced maps are necessary for constructing waypoints.

Figure 5 – Tactical Commander reviews flight video

Setting up specific waypoints to define the flight plan is a required step and took the longest amount of time during setup. MLB has implemented some automatic waypoint generation methods, and the SWAT leaders felt that some SWAT-oriented flight plans with automatic waypoint generation would eventually be necessary. However, it should be pointed out that this site was in a mountainous region and an automatic process would have likely needed modification or at least double-checking by an operator.

Normally, the SWAT leaders are located at the command post, which is very often in the middle of a congested urban area. UAV takeoff and landing will typically need to occur at a separate location. For instance, nearby open fields could be used, such as the park shown in Figure 1. Consequently, either an additional ground station must be located at the command post or the UAV

operator must move between the launch area and the command post after the UAV is airborne. Either solution would incur further operations issues to be studied and addressed.

In the future, UAV use would probably be the responsibility of an additional person in the command post, rather than add that responsibility to an existing command post position. The new job would be to monitor the information and report what happens to the tactical commander, much as the other tactical dispatchers do now. At least at first, one more additional person would be responsible for the operation of the airplane itself. However, depending on the workload distribution that develops over time, these two jobs could conceivably be condensed into one.

Conclusion

This research highlights the promise and the challenges of utilizing autonomous robots in SWAT applications. Some of the findings require fundamental research to advance the current state of the art, while others point to overlooked factors that should be considered during robot design.

The best use of currently available autonomous robots in a SWAT application appears to be a reliable, easily deployed system that increases situational awareness with minimal impact on the SWAT team's workload. This implies that the robot's mobility must be predictable rather than "intelligent," must be based on onboard sensing, and easily directed by commanders. In addition, information gathering must be highly refined, with georeferenced data available in a format that is readily combined with a team's existing infrastructure, typically hardcopy maps. Thus, the robot should be designed as a data gathering system rather than just a mobile vehicle with a camera.

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