Distributed Tactical Surveillance with ATVs

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ABSTRACT

In Carnegie Mellon University's CyberScout project, we are developing mobile robotic technologies that will extend the sphere of awareness and mobility of small military units while exploring issues of command and control, task decomposition, multi-agent collaboration, efficient perception algorithms, and sensor fusion. This paper describes our work on robotic all-terrain vehicles (ATVs), one of several platforms within CyberScout. We have retrofitted two Polaris ATVs as mobile robotic surveillance and reconnaissance platforms. We describe the computing, sensing, and actuation infrastructure of these platforms, their current capabilities, and future research and applications.

Keywords: Robotics, Multi-Agent Collaboration, Reconnaissance, Surveillance

1. INTRODUCTION

Reconnaissance, surveillance, and security operations are time-consuming, tedious, and potentially dangerous, but critical to the success of military and other organizations. The goal of Carnegie Mellon University's CyberScout project is to create mobile robotic technologies that extend the sphere of awareness and mobility of an individual or group performing such operations. By increasing sensory "reach", giving the robots a significant degree of autonomy, and providing the ability to task multiple platforms as a single logical entity, CyberScout seeks to augment human capabilities, reduce exposure to risk, and present timely, relevant information to the user.

Within CyberScout, we have developed several robotic platforms covering a range of sizes and capabilities. The largest of these and the one described in this paper is a robotic All-Terrain Vehicle (ATV). We have retrofitted two Polaris ATVs (named Lewis and Clark, after the famous explorers), automating their throttle, steering, braking, and gearing functions and giving them computation for control, navigation, sensing, and communication. Users task, control, and monitor the ATVs and other platforms which make up CyberScout through CyberRAVE (Real and Virtual Environment), a software framework and graphical user interface which enables rapid configuration and prototyping of cooperating groups of real and virtual robots. When no human user is present, CyberRAVE allows robots to continue to operate in autonomous mode.

The ATV is a particularly suitable platform for augmenting mobility due to its ability to carry a person for a distance of approximately 200 miles on a tank of gas. For this purpose, our ATVs can operate in manual mode, which allows actuation of the four vehicle functions (throttle, steering, gearing, braking) via R/C joystick or wireless Ethernet, as well as in autonomous mode. In autonomous mode, the ATV has a variety of behaviors which allow it to navigate and explore its environment.

In the past decade there has been considerable effort to develop autonomous robotic vehicles to conduct random patrols, assess barriers, detect intruders, reconnaissance, surveillance, building entry, target detection, building or terrain mapping, and explosives neutralization. Mobile robotic platforms with the above capabilities will improve a commander's ability to counter threats, lessen risks to personnel, and reduce manpower requirements.

In the literature several experimental platforms with some of the above requirements have been reported. Sandia National Laboratories developed the Surveillance And Reconnaissance Ground Equipment (SARGE) [1] robotic vehicle for the US DoD. SARGE is a teleoperated robot for battlefield survellance applications without computing power to support autonomous navigation or vision processing. SARGE was built around a Yamaha Breeze 4-wheeled all-terrain vehicle. It was used for early user appraisal to aid the US Army and Marines in developing tactics

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and doctrine for robotic ground vehicles in tactical surveillance and reconnaissance missions. Similar teleoperated battlefield mobile robot research sponsored by US DoD is reported in [2, 3, and 4]. SARGE II is a second generation of SARGE with a multiprocessor computing system. SARGE II employs differential GPS (DGPS) for autonomous navigation and neural network processing of Sandia's Laser Radar (LADAR) range images for local obstacle detection and avoidance.

Robotic System Inc. [5] developed the Mobile Detection Assessment and Response System-Exterior (MDARS-E) for the US Army's Physical Security Equipment Management Office. The MDARS-E platform is built around a diesel-powered, hydrostatically driven vehicle. Its navigation employs a differential GPS receiver integrated with inertial and landmark referencing sensors. MDARS-E uses low-bandwidth radio–frequency communications to transmit its real–time position for display on a site map. MDARS-E uses innovative video compression, image processing, and radar and spread spectrum techniques.

In [6] an Autonomous Robot for Surveillance Key Applications (ARSKA) is presented. This UGV is built around a Honda TRX 350 all–terrain vehicle. ARSKA is equipped with ultrasonic sensors for contour–following and obstacle avoidance. Two positioning systems have been used with the vehicle: an external optical measurement device called a tachymeter, and differential GPS (DGPS). ARSKA can be controlled using a ground station. The basic functions of the ground station are task preparation and monitoring and on–line telecontrol of the vehicle. ARSKA has been used to guard an Army storage area.

Although some of the reviewed autonomous robotics vehicles have demonstrated minimal supervised autonomy, it is achieved at the expense of costly and power-intensive sensors (e.g. optical range imaging sensors) and high-bandwidth, bulky teleoperated command and control ground stations. In general, a high degree of autonomy requires considerable computing power. The path planning algorithms used generally require apriori knowledge of free paths and obstacles in the environment, which of course are not always available. Another major drawback is that the platforms' autonomous capabilities are not designed in a modular framework. It is therefore not easy to systematically incorporate higher levels of autonomous capabilities and new sensors without a significant redesign of the autonomous control architecture. Finally, most of the reported work has concentrated on single platforms, whereas surveillance and reconnaissance tasks benefit from the use of multiple platforms.

In CyberScout, emphasis is placed on using relatively inexpensive ($<$ \$2000), passive sensors and computationally efficient perceptual algorithms. Considerable research effort is also directed towards developing a distributed command and control framework to accomplish multi-agent collaboration, a critical component in performing mobile robotic surveillance and reconnaissance.

The rest of this paper is organized as follows. Section 2 describes the vehicle retrofit, including actuation, computing, sensing, communications, and power aspects. Section 3 describes the low-level vehicle control algorithms. Section 4 outlines current vehicle capabilities and future research directions, and Section 5 presents conclusions.

2. CYBERATV PLATFORM

We have created two Unmanned Ground Vehicles (UGV) by retrofitting two Polaris Sportman 500 ATVs figure(1). The four vehicle functions most critical for autonomous control are throttle, steering, gearing, and braking. Each of these is provided with a mechanical actuator controllable by a computer. The computing architecture is two-tiered: a PC/104 controls vehicle locomotion, while a group of three PCs in a custom housing perform perception, planning, and communications. A generator provides auxiliary power.

2.1. Actuation

The throttle function is actuated by an R/C servomotor, whereas the automatic steering, braking and gearing functions are actuated hydraulically. Turning the steering requires considerable torque when the vehicle is stationary or moving at low speed, and the amount of space for mounting actuators on the steering is fairly limited. A hydraulic actuator was therefore chosen due to its high power-to-weight ratio and resulting compact size relative to a comparably powerful electric motor. The same hydraulic system was then used for gearing and braking.

Figure 1. Picture of ATV Clark

2.1.1. Steering Actuator

The steering actuation consists of a 4.5" hydraulic piston aligned parallel to the steering push rod on the right front wheel (from the rider's view). The rod end of the cylinder is attached to the suspension crank arm. The cap end of the cylinder has a trunnion mount and is attached to the ATV chassis. A proportional directional control valve is used to control hydraulic flow to the steering cylinder. The flow output of the valve can be affected by a variable voltage input command between 0 and 10 volts [7]. The slew rate, rather than the position, of the steering is roughly proportional to this command. A resistive linear potentiometer is incorporated at the cap end of the cylinder to provide feedback (0–5volts) and is connected to a DM5416 Real–Time Devices analog/digital I/O board on the PC/104 stack.

2.1.2. Gear Actuator

Two linear hydraulic actuators are mounted back to back for shifting into neutral, high and reverse gears. The two cylinders are connected to the gear selection assembly by an adjustable rod. Neutral position corresponds to cylinder 1 retracted and cylinder 2 extended, high gear corresponds to cylinder 1 retracted and cylinder 2 retracted, and reverse gear corresponds to cylinder 1 extended and cylinder 2 extended. A three–way control valve is used to control the hydraulic linear actuators [7]. The existing ATV gear selection light is used for feedback and is connected to a DM5416 Real–Time Devices analog/digital I/O board on the PC/104 stack.

2.1.3. Brake Actuator

The pre-retrofit ATV braking system consists of a single-lever, all-wheel hydraulic disc brakes and a hydraulic rear foot brake. In the retrofit, only the rear brake is actuated, using a low–profile air/oil cylinder. A directional control valve is used to control the brake cylinder. This nominally provides for only on/off braking, but the brake can be pumped, or cycled, at different rates in order to provide intermediate levels of braking. There is no explicit feedback from the brake.

2.1.4. Hydraulic System

The hydraulic pump is a Parker series D gear pump equipped with an integral four–quart reservoir and a system relief valve. The pump is driven by a NEMA 56C frame single–phase AC motor which uses a 120 V AC input. The pump motor is controlled by a single solid–state AC contactor located inside the electric enclosure [7]. To reduce heat and power, the pump circuit includes an unloading valve circuit to dump fluid at low pressure when high pressure fluid is not required. A 2–quart piston-type accumulator is included in the circuit to reduce pressure instabilities.

2.1.5. Throttle Actuator

The ATV is equipped with a 4–stroke, liquid-cooled engine with a 34mm Mikus carburetor which is regulated by a throttle plate. A Futaba R/C servomotor is used to accomplish the opening and closing of the throttle plate via two cables. One cable connects the servo to the throttle control lever on the handlebar, while a second cable connects the servo to the throttle plate. Each cable is passed through a friction clamp that holds the cable in place and also provides a means to adjust the length of the cable. The throttle plate setup incorporates a torsional spring, which applies a closing torque on the throttle plate sufficient to back drive the servo to idle throttle position when power is turned off. The choice of an R/C servo for throttle actuation is based on its low cost, small size, internal closed-loop position control, low power consumption and easy control signal generation. Speed feedback is obtained via a tach generator mounted in the gearbox. The tachometer is a Servo–Tek SB–763 – 2A, designed for use in applications requiring an output signal between 1 and 10 volts/1000RPM. The output of the tachometer is connected to a DM5416 Real–Time Devices analog/digital I/O board on the PC/104 stack.

2.2. Computer System

The computational architecture is two-tiered: locomotion (low-level processing) is performed by a PC/104, while planning, perception, and communications (high-level processing) are performed by a set of three networked PCs in a custom housing mounted on the front of the vehicle. We concentrate here on the low-level, locomotion processor (the PC/104). The PC/104's economy of size (4 by 4-inch cards), low power requirements, and mechanically rugged design are well suited for outdoor applications. Further advantages are the availability of components from a variety of vendors and the ability to use virtually all of the program development tools used for IBM PC's.

The configuration of the PC/104 employed includes four boards from three different vendors:

- One Versalogic VSBC–2 CPU featuring a 32–bit, 133MHz, 5x86 CPU chip. Its performance is equivalent to a Pentium 75 MHz machine.
- One WinSystems PCM–COM4A serial interface board . This board is a 4–channel serial INS8250–compatible PC/104 module. Each channel supports RS–232, with RS–485 and RS–422 as options.
- One WinSystems PC/104 video board, the PCM-FPVGA. It supports standard VGA CRT output as well as a variety of flat panel displays using optional flat panel adapter (FPA) modules. Other options include multi-video display capability, PC video input, and NTSC video output.
- One DM5416 analog/digital I/O board from Real-Time Devices. The DM5416 has 8 differential or 16 single-ended analog input channels with an input range of -10 to +10 volts, 8 bit–programmable digital I/O lines with advanced digital interrupt modes, one 16–bit digital-to-analog output channel, 8 port–programmable digital I/O lines, two 16-bit timer/counters, and an 8 MHz clock.

2.3. Sensors

Navigational sensing is performed by a 20–cm resolution NovAtel DGPS unit. Perceptual sensing is currently restricted to vision, which we are trying to exploit to the fullest due to its passive, unobtrusive nature. Currently each vehicle is equipped with five cameras, a panning stereo pair in front for obstacle avoidance and mapping, and three pan/tilt cameras for surveillance, one each located at the front left, front right, and rear. Stereo vision is employed to have a 3–dimensional understanding of the environment to perform free space mapping, thus enabling obstacle detection and path–planning. Further details about CyberATV's perceptual sensing can be found in [8].

2.4. Communications

Communications between the low-level and high-level processors are currently via a serial cable, but can be upgraded to wired Ethernet if increased bandwidth is desired. Communications with other platforms and with remote users are performed via wireless Ethernet using 915MHz Wavelan technology.

2.5. Power System

Consideration was given to adding a take-off to the vehicle clutch in order to provide power for the systems added to the vehicle by the retrofit. We discarded this solution, however, for two reasons. First, it was mechanically infeasible due to excessive motion of the clutch drive shaft. Second, the amount of power available from the alternator was projected to be insufficient. As a result, a 2.5kW Honda generator was mounted on the rear of the vehicle to provide auxiliary power.

The generator provides two 120V AC, 15A outputs. One of these powers the hydraulic motor. The other is converted to 24V, 12V, and 5V DC for use by the sensors, relays, optoisolators, and hydraulic valves. 5 volts are supplied separately to the PC/104 by the ATV's battery via a 12-to-5V DC converter.

3. LOW-LEVEL CONTROL SYSTEMS

The automatic control of gearing and braking involves the straightforward setting of various hydraulic valves. Speed/throttle and steering control, however, involve interesting challenges which are detailed in this section.

3.1. Speed Control

Since the ATV is equipped with cameras for navigation it is essential that the vehicle moves smoothly at fairly low speeds that will allow real-time processing of images. The two main challenges in designing an effective speed controller for the ATV are

- the lack of a complete mathematical model for the engine.
- the highly nonlinear nature of the engine dynamics, especially for the target low speed range of 3–30MPH.
- the belt slippage of the Automatic Polaris Variable Transmission (PVT) at low speeds.

Each of these factors makes the use of classical control strategies such as PID control ineffective. Using experience and data collected from extensive experiments conducted on the ATV throttle mechanism, an adaptive fuzzy throttle control algorithm was designed [9]. A candidate Lyapunov function was employed in the adaptive law synthesis to ensure convergence. The adaptive fuzzy throttle control produces smooth vehicle movement, robustness with respect to varying terrain, and commanded speeds in the range 2MPH to 30MPH. Figure(2) depicts the ATV speed response to a selected speed.

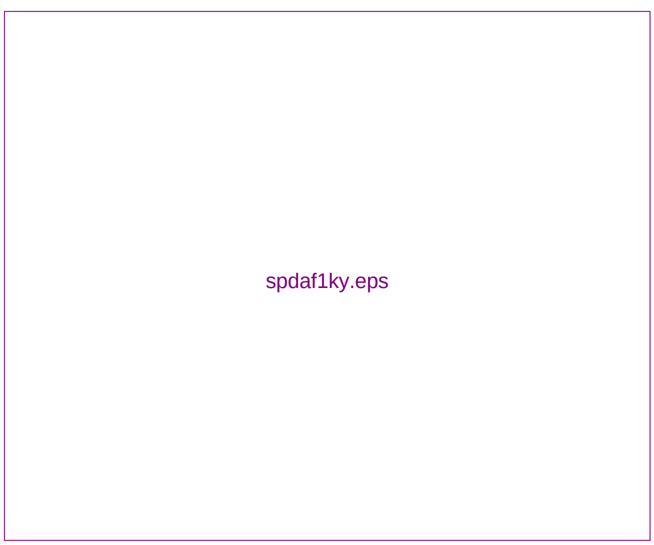

Figure 2. ATV speed response for adaptive fuzzy throttle controller for 2.9MPH (1.3m/s)

3.2. Steering Control

The objective of the steering control system design is to provide precise locomotion, pointing, and posture and robustness to external disturbances. A simple initial design was bang-bang control. This resulted, however, in large errors and instability when small steering angles were commanded. A fuzzy PD controller was then developed using data collected and experience gained from the bang-bang control scheme. The fuzzy PD algorithm was found to produce smooth control and fairly accurate pointing for navigation and visual tracking. Figure(3) depicts the ATV steering reponse to commanded steering angle.

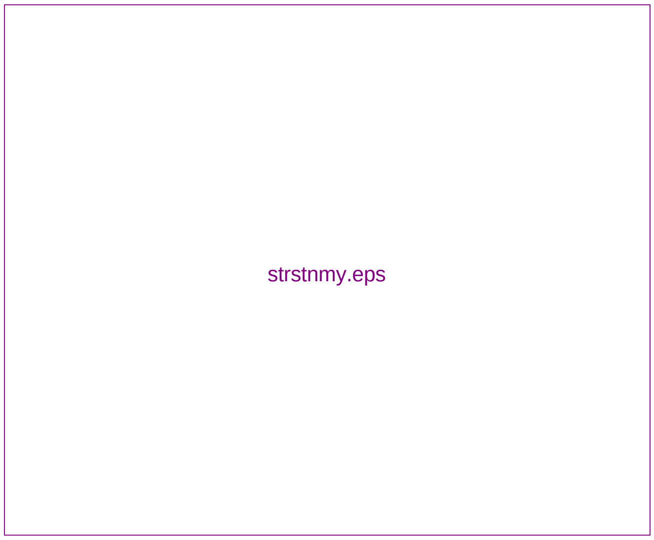

Figure 3. ATV steering response for Fuzzy PD steering controller

The described steering control was initially applied to the voltage feedback received from the steering potentiometer. Due to mechanical hysteresis in the steering, however, this voltage is not linearly related to the actual steering angle. Based on measurements characterizing the steering hysteresis loop, we have developed a steering model which establishes the nonlinear relationship between voltage and angle (see Figure(4), in which pixels correspond to steering angle). This model allows us to reduce steering angle error from as great as 5 degrees to +/-1 degree.

4. CURRENT CAPABILITIES AND FUTURE WORK

We have demonstrated the following capabilities on the ATVs:

- remote manual control using various input devices (R/C joystick and laptop/wearable computer via wireless Ethernet).
- autonomous GPS-based waypoint navigation.
- autonomous convoying based on visual tracking.
- sidewalk and path-tracking.
- potential-field obstacle avoidance.
- robust personnel/vehicle classification using vision.
- window detection and classification for building surveillance.

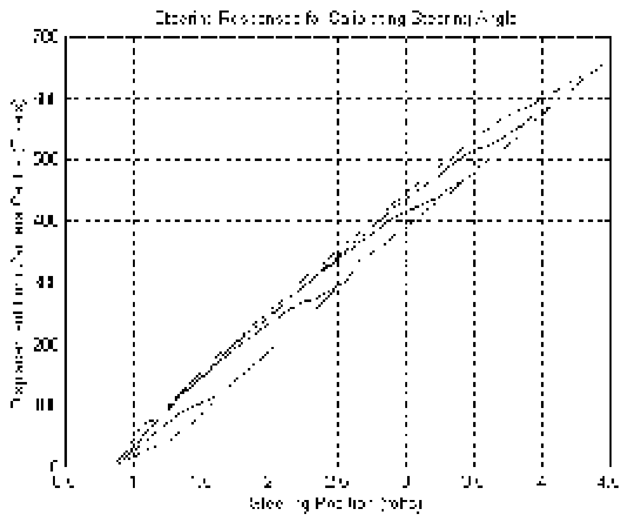

Figure 4. Steering hysteresis loop

Our current and future work involves integrating the above-described capabilities in order to give the ATVs the ability to conduct a building "stakeout". In this scenario, a lead vehicle travels in autonomous mode towards a site whose general location is known, using DGPS, sidewalk tracking, and landmark-based tracking as appropriate and available. When it reaches a location from which building surveillance can begin, it communicates its position and relevant information about the path it traversed to the stay-behind vehicle, which then joins it at a location appropriate for good coverage of the building of interest. Coverage is adjusted in response to activity at the site. The ATVs will simultaneously conduct window detection and personnel/vehicle classification, as well as perform correspondence in order to track targets of interest. Using CyberRAVE, a remote user can intervene at any time in order to view information, manually adjust the action of an ATV, or provide tasking.

5. CONCLUSIONS

We have created two mobile robotic platforms with the computing, sensing, and command and control needed to conduct largely autonomous reconnaissance and surveillance in the context of small unit operations. The following capabilities are key to this development:

- Effective low-level control of throttle and steering to handle difficult nonlinearities
- Navigation using GPS in combination with stereo vision for obstacle avoidance and landmark tracking
- Efficient perceptual detection and classification algorithms that can run on standard PCs and use relatively inexpensive, passive sensors (cameras)
- A modular, distributed, agent-based command and control architecture that allows us to easily incorporate additional algorithms, sensors, and vehicles without redesign

Future work will concentrate on collaborative strategies for the accomplishment of a variety of reconnaissance and surveillance tasks.

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