Cyclops: Miniature Robotic Reconnaissance System

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I. ABSTRACT

Miniature mobile robots are desirable for military applications because of their ability to function covertly in highly constrained environments. However, work on such tiny robotic systems has been hampered by the difficulty of packaging locomotion, sensing, computing and power subsystems into diminutive spaces. This paper presents the design and initial prototype of a miniature mobile robot designed to carry out surveillance and reconnaissance missions in an urban environment. This initial prototype is spherical in shape, with a diameter of 5.5 inches, and weighs only 4.5 pounds. A novel inertial steering system, along with the robot's robust control and communication systems, make it useful for covert video surveillance and reconnaissance in tightly constrained spaces.

II. INTRODUCTION

A clear need for mobile surveillance systems exists in several lines of work. The most obvious of these is police or military actions in urban areas. Remote surveillance systems remove the systems' operators from harm's way, giving them the opportunity to survey a potentially dangerous situation from a distance. Mobile robots with video transmission capabilities can also be used effectively as expendable "point men", giving advance information about enemy positions in active combat situations.

The motivation for this design came from the desire to produce a robot small and light enough to be hand-carried, yet capable of carrying out at least one hour of mobile, semi-autonomous video surveillance of a given indoor area. To that end, we have designed a small spherical robot (5.5 inches in diameter, as mentioned above) with the characteristics listed in Table 1. Section IV explains in detail how we satisfied these size and power constraints while still giving the robot significant navigation and surveillance abilities.

Figure 1: Cyclops in an outdoor setting.

Component	Description
Robot Body Shell	5.5" diameter transparent acrylic sphere, with vertical tread strip
Locomotion	2-DOF mobility provided by forward/reverse roll mechanism with inertial steering
Control	Custom network of three embedded microcontrollers with RF-based serial link to operator controller unit
Navigation	Ceramic gyro, electronic compass linked to dead-reckoning microcontroller module
Video Telemetry	CCD camera with RF video transmitter
Power	Lithium-Ion primary battery pack, ~1.5hr. life for normal operation

Table 1: Cyclops System Characteristics

III. SYSTEM APPLICATIONS

Two main applications were initially projected for Cyclops, and both are available in the prototype robot. The system functions either in a forward reconnaissance role, gathering information in unknown (and probably unfriendly) environments, or as a patrol agent, scanning an already secured area while following a pre-set patrol route through an indoor space. Section IV presents the functional capabilities which allow Cyclops to fill these two roles; first, let us look at each in a bit more detail.

Robotic scout vehicles have been proposed and even implemented for some time; what makes Cyclops uniquely effective in many situations is its small size (which is a positive attribute in hostile environments) and its ability to be deployed into small spaces (like ventilation ducts or ceiling crawl spaces) where larger systems can not operate. Furthermore, a soldier can toss the system through an opening (such as a blown-out window or doorway) through which an ordinary-sized robot could not locomote. This is not a system in which sensing and computing have been sacrificed in the pursuit of miniaturization, however. On the contrary, Cyclops provides full-frame-rate video to the operator via an RF interface, and is invaluable in this forward video surveillance role.

Just as importantly, the unobtrusive size and locomotive capabilities of Cyclops enable it to be used to covertly patrol an area which has already been secured. The robot contains a suite of inertial dead-reckoning devices which allow it to calculate its compass heading at a rate of 5Hz and to measure the distance it has rolled with accumulated errors smaller than one percent. These two measurements, heading and distance traveled, can be combined to allow Cyclops to carry out sophisticated motion patterns across a complicated indoor area. One application of this capability is a method of “recording” a patrol route as commanded manually by a human operator, and then “playing back” that patrol route autonomously by the robot. In fact, nearly any autonomous navigation algorithm which relies on accurate dead-reckoning information can be implemented using Cyclops. Future work will focus on porting navigation systems like STRIPE and D* to this platform.

IV. SYSTEM OVERVIEW

We will discuss the three primary subsystems (Locomotion, Control, and Sensing) of the Cyclops robot in separate subsections. A CAD overview of the system with its shell removed can be seen in Figure 2, along with the actual prototype in Figure 3.

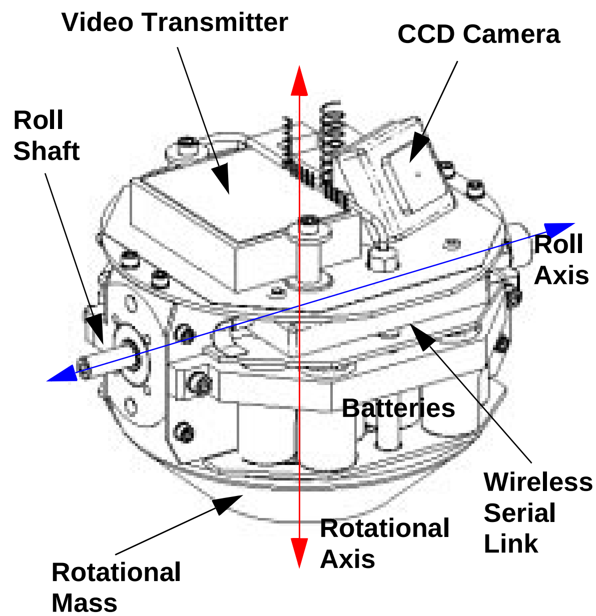

Figure 2: A CAD rendering of the Cyclops prototype.

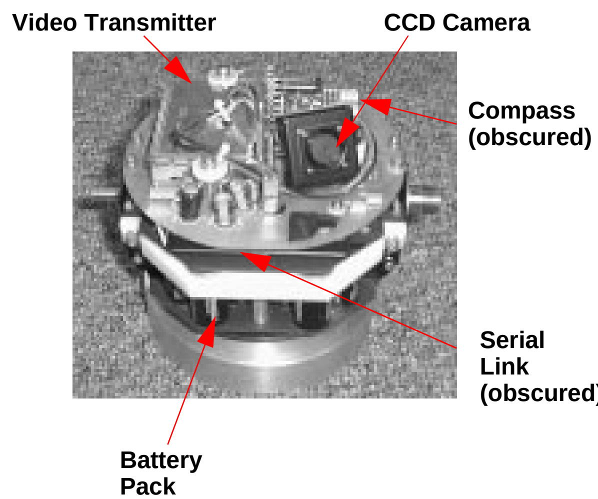

Figure 3: The Cyclops prototype, without its external shell.

4.1 Locomotion

Cyclops has two degrees of freedom in its locomotion system: it can pivot in place along its vertical axis using a rotating inertial actuator, and roll forward and backward along a fixed horizontal axis via a small motor and gearhead. Figure 4 shows a CAD rendering of the locomotion mechanism.

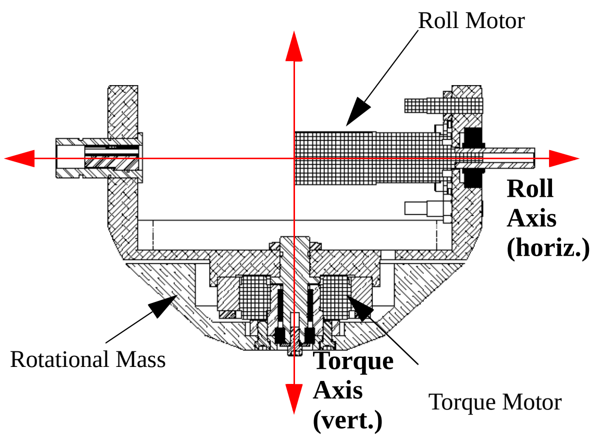

Figure 4: The structural "yoke", with roll and torque mechanisms attached.

4.1.1 Rotational Actuator

The rotational mechanism consists of a large, conical mass (the "Rotational Mass" in Figure 4, shown in close-up in Figure 5) which is attached directly to the output shaft of an electrical motor powerful enough to accelerate that mass from rest to full velocity in a few seconds. The voltage applied to that motor is controlled proportionally by one of the three onboard microcontrollers linked to a standard H-Bridge motor driver chip. In essence, we can control the amount of torque applied to the mass by varying the motor control signal output from the microcontroller.

Figure 5: A view of the rotational mass from the underside of Cyclops.

The pivot-in-place motion is achieved by applying a certain amount of torque to the mass at rest; the reaction torque in the opposite rotational direction is applied between the robot body and the ground, and the robot turns in place. The primary problem with this method of actuation lies in solving for the torque needed to turn the robot a specified number of degrees. We have thus far only implemented an approximated method which calibrates the system with respect to the frictional characteristics of a given surface and then issues a series of small "torque pulses", servoing the robot closer and closer to a desired heading. Future work on this mechanism will be directed toward implementation of a control scheme that allows smooth, continuous changes in heading rather than this pulsed motion.

Two of the onboard sensors serve as control inputs for the so-called "torque" system (that is, the rotational actuator). A miniature ceramic gyro gives information on angular rate at nearly 10Hz, and an electronic "flux-gate" compass provides heading data at 5Hz. The gyro is used to provide feedback data for producing smooth rotations, and the compass feeds heading information back to a dead-reckoning module. Figure 6 presents a simplified block-diagram view of this subsystem.

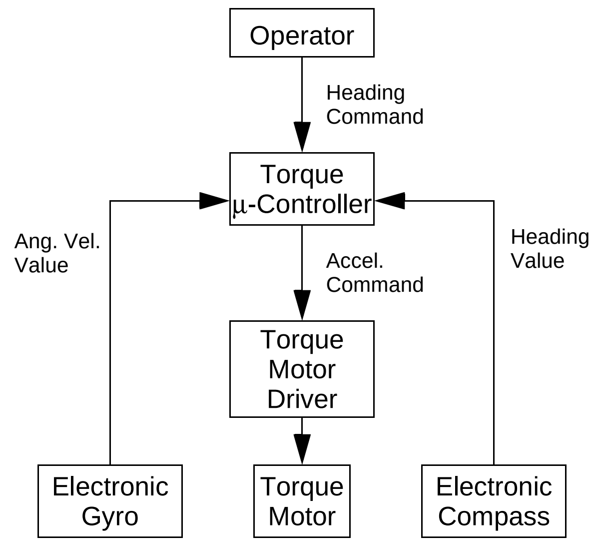

Figure 6: Schematic view of the Cyclops rotational actuator subsystem

4.1.2 Roll Actuator

The mechanism which causes Cyclops to roll with respect to its horizontal axis is considerably simpler, in design and in control complexity, than is the rotational mechanism. A small motor and gearbox are embedded along the center of the robot, anchored to what is thought of as the interior "body" of the system. The gearbox output shaft is attached through a slip clutch (to protect the gearbox from high externally-applied torques) to the outer shell of the robot. The low center-of-gravity of the inner body allows the roll motor to drive the robot in one direction by applying torque to the outer shell in the opposite direction. Thus, for the roll motion we count on the shell *not* to slip with respect to the ground, but for rotations we expect exactly the opposite. Some experimentation was required to identify "tread" materials with the desired properties; we chose a teflon-coated friction tape.

The control scheme for the roll motion is rather simple. As in the other mechanism, a microcontroller linked to a standard H-Bridge driver controls the power applied to the motor. A custom Hall-Effect Sensor-based encoder counts revolutions of the shell with respect to the body; this information is fed back to the control loop to give us highly accurate roll positioning. Preliminary experiments indicate that the roll module has a positioning accuracy of approximately one percent (due to encoder resolution and shell slippage) and can measure distances of more than 100 kilometers before rolling over the internal 24-bit counter. With a maximum linear speed of roughly 40 centimeters per second, this roll mechanism is highly capable. In particular, during one hour of typical battery life, the system can cover nearly 1.5km of straight-line distance. Figure 7 shows the primary structure of this subsystem.

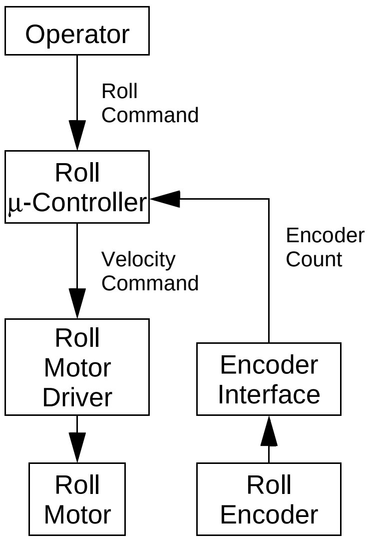

Figure 7: Schematic view of the Cyclops roll actuator subsystem

4.2 Control and Power

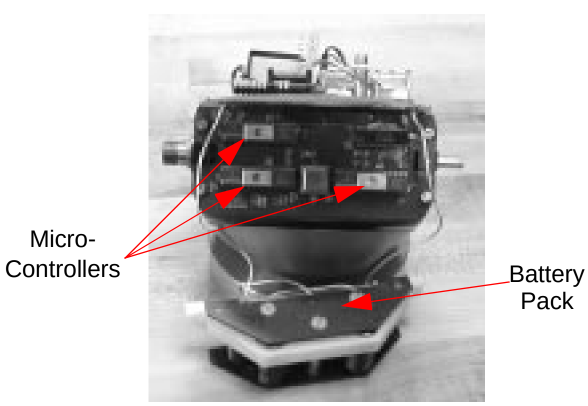

Figure 8: The control board for the Cyclops prototype.

The Control subsystem of Cyclops consists of three microcontrollers and a miniature wireless serial transceiver (dubbed the “μT”), linking the robot to the operator’s remote control station (see Figure 9 for a representation of the flow of commands). These microcontrollers are all PIC16C73A models produced by MicroChip. All three live on a custom processor card (Figure 8), which also has connectors for power and signals from the control peripherals (gyro, compass, serial transceiver, etc.).

The software which handles the tasks of rolling a particular distance, turning to a desired heading, transmitting status information, and receiving commands from the operator is distributed across these three processors. One is dedicated to controlling the “torque” motion (a formidable task in itself), one is in charge of roll motion, and one chip monitors the asynchronous communication between the robot and the operator as well as between the two motion control processors. A network based on the I2C bus (originally from Philips) allows the three to communicate among themselves.

The extensive range of on-chip I/O options allowed us to easily interface the three controllers to the various peripherals. Each of the peripherals is listed in Table 2, along with the corresponding interface method and the processor (torque, roll or μT) responsible for handling that device.

Peripheral	**Interface**	**Processor**
Wireless serial link	RS-232, TTL-level voltages	μT
Ceramic gyro	Analog 0-5V	Torque
Electronic compass	SPI, TTL-level voltages	Torque
Encoder	8-bit data, 3-bit control bus	Roll
Status LEDs	TTL	All
Motor current feedback	Analog	Roll, Torque

Table 2: Interfaces for Control Peripherals

Cyclops’ internal power system is completely self-contained and requires no external tether to a power source. Two 18V battery packs, each comprised of 6 off-the-shelf Lithium-Ion primary cells (originally designed for use in cameras), are connected in parallel to supply high peak current drains for the torque unit. Preliminary experiments show the battery life to be between one and two hours, depending on the ratio of time spent locomoting to time spent in stationary surveillance mode. Future work will focus, in part, on ways of extending the battery life, including the use of custom battery packs (such as the recently-developed prismatic Li-Ion packs, which have extremely dense packing ratios), and minimization of power drains for the existing electronic components.

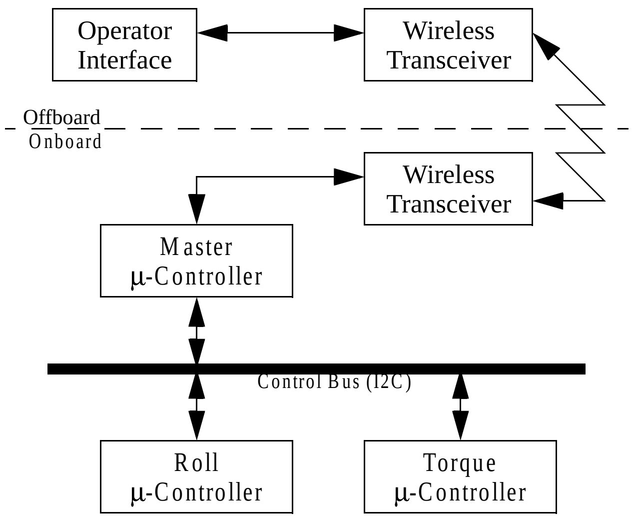

Figure 9: Flowchart view of the Cyclops control system

4.3 Sensing

The term “Sensing”, in this context, will refer to the surveillance sensors provided on Cyclops, rather than to the control sensing, which was discussed previously.

The primary surveillance sensor for the Cyclops system is a subminiature 1”x1”x0.5” black-and-white CCD camera, with a pinhole lens. The output of this camera is beamed, by a miniature wireless video transmitter, to the operator’s control station. The camera provides approximately a 30-degree field of view (see Figure 10), which has proven in initial tests to be sufficient for remote teleoperation of the robot. In addition, the camera can be panned around a scene smoothly by use of the rotational actuator.

We are in the process of adding a high-resolution color CCD camera of similar size to this system, which will greatly enhance the quality and value of the visual data stream provided to the operator.

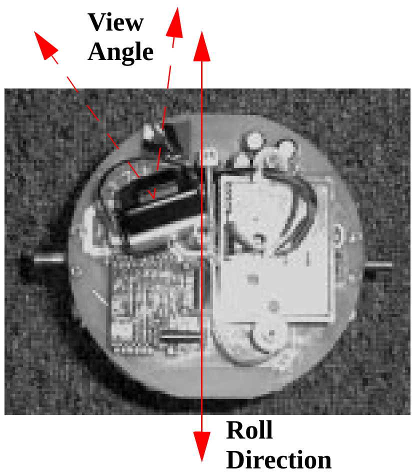

Figure 10: The viewable angle from the Cyclops prototype with respect to the direction of travel.

V. ACKNOWLEDGEMENTS

This project was funded by the Defense Advanced Research Project Agency (DARPA) under Contract Number DAAL01-97-K-0165. The technology we have produced is intended to compliment the Pandora mobile surveillance system developed under the same contract. We would like to further acknowledge the support of Scott Boehmke, whose knowledge of electronic devices has made the development of this miniature system possible. Patenting of Cyclops is pending.

VI. FURTHER DEVELOPMENTS

Two new versions of the Cyclops system are under development in the summer of 1998. These systems have similar capabilities to the prototype system described here, but include miniaturized versions of the high-resolution omnispherical imaging system developed by Shree Nayar at Columbia University, as well as high-res, high-power video transmitters. These systems have the ability to capture fully immersive video streams of their surroundings, making them even more useful for urban operations.

Additionally, CMU and a commercial venture continue to develop the Cyclops system with an eye toward making improvements in size, power, and ruggedness. A design for a 4”-diameter Cyclops, with improved mobility and sensing, has been completed.

VII. REFERENCES

[1] Chemel et. al, “Cyclops- Design of a Miniature Robotic System”, CMU RI Tech Report, to be submitted, Winter 1998.

[2] US Army Research Laboratories, “Pandora: A Robotic System for Operations in Urban Environments - Final Design Document”, official contract report submission, March 1998.