The Pipe Crawler

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Abstract

A number of experimental studies have explored the concept of robots that travel inside pipe networks for purposes of inspection, cleaning, or repair. The authors undertook the design and implementation of such a robot as a senior Engineering Design project with the aim of investigating several new variations on this idea. A teleoperated platform capable of negotiating pipe elbows and vertical sections is presented; this mobility is made possible using a set of free-spinning wheels, pitched like the blades of a turbine, which are rotated coaxially with the pipe, providing forward propulsion in the manner of a turning screw. The project also features a method of navigation using wheel odometry to determine distance and recently developed IMEMS (Integrated Micro Electro-Mechanical Systems) gyroscopes to measure yaw, pitch, and roll. To aid in the troubleshooting of pipe defects, this system presents the operator with the current location of the robot and a map of the path it has traveled. Although some of the project goals were not completely fulfilled, efforts to correct any remaining deficiencies are ongoing.

Acknowledgments

Team six is most indebted to its principal advisor, Mr. Tom Kelly, Director of Technical Services for Florida Atlantic University. Mr. Kelly's incredible diversity of knowledge on such widely-separated topics as metal fabrication, communications, and microprocessors provided invaluable guidance; even more important was his unquenchable energy and apparently endless ability to tolerate our presence in his lab, which was to house the project from beginning to end.

Although he arrived in the last weeks of the semester, the assistance of Jeff Webb, master machinist of FAU Mechanical Engineering, proved invaluable. Several critical parts could not have been made without his extensive experience, patience, and skill. Would that he had been here sooner.

We must honor the generous attitude of Analog Devices, Inc., towards the poor and downtrodden – especially those college students that could not afford numerous gyroscopes, accelerometers, and development boards for all of these without Analog's splendidly open policy of free evaluation samples.

However, it is also necessary to thank those whose work helped to alleviate the effects of Analog's other policy, that of rigorous insistence on designing surface-mount devices. Leading the efforts to get those devices connected to something useable were Jim Paolantonio of Sensormatic Electronics and John Marsinka, solder-wizard of the FAU HDTV Lab.

Kirk Little, student and de facto machinist of the Department of Mechanical Engineering, deserves our praise for, despite already working twice as long as he received compensation for, finding the time to do several important machining operations for us.

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Finally, we should acknowledge the three coordinating professors of the FAU Engineering Design class, Dr. Bassem Alhalabi, Dr. Ming Huang, and Dr. Daniel Raviv, for pointing the way toward funding, providing an opportunity for the members of team six to meet, and facilitating the development of this project with advice and encouragement.

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I. Introduction

Statement of the Problem

Plumbing networks, like any other structure, are vulnerable to damage from various sources: thermal cycling (especially when ground freezes around the pipe), mechanical impacts or vibrations, corrosion, etc. Pipes can fill or clog with debris, sediments, or, as with the zebra mussel infestation in the northeast United States, living organisms. Smaller fluid systems, such as those serving residences, may be repaired with easy, low-cost methods; in many cases it may be best to simply replace the pipes. Operators of larger, complex systems, however, frequently need some better way of dealing with plumbing failures. For instance, it is not cheap to replace large diameter pipes; it is even worse if hundreds of meters of pipeline must be unearthed to determine which section is responsible for a drop in pressure. Preventative inspection can be another difficult requirement of industrial users: critical systems or those serving sensitive machinery may have to be inspected periodically, to ensure the safety of human users or to prevent damage to expensive systems.

It is possible to detect cracks or corrosion thinning in plumbing with various methods of non-destructive testing, such as eddy-current or ultrasonic sensors, but these require access to the outside of the pipes; difficult and costly in many situations, such as long, buried lengths. Furthermore, this does not address the problem of clogging or fouling. In many such applications, an internal inspection solution may be preferable.

If a robot were designed to travel the length of the pipe and conduct such inspections, it might have other uses as well. For instance, it could carry a cleaning mechanism or manipulators to remove foreign objects. It could pull electrical or communications cables through conduits. Such a machine has potential as a life-saving tool also: when buildings collapse, due to earthquakes or other disasters, the internal pipe network may still be navigable for a pipe-crawling robot, which could carry video cameras or microphones to locate signs of humans trapped below.

Background

A survey of existing pipe-inspection robots has been conducted to assess the feasibility of this project and to determine what might be the best approach to accomplishing them. It was found that several pipe-inspection robots have been constructed experimentally; some are even commercially available products. The simplest of these (and consequently the most numerous in the market) are platforms resting on wheels or tractor treads underneath. Such robots suffer from an inability to negotiate vertical sections of pipe. In addition, many have limited steering abilities and may be too long to pass through even horizontal elbows. Envirosight LLC offers a series of such robots in their line of ROVVER inspection crawlers; these are tethered four- or six-wheeled vehicles which carry a range of video cameras and are available in sizes as small as 4 inches (Ref. 1).

More advanced pipe inspectors are capable of traveling through vertical pipes. One of these, developed by RoboProbe Technologies Inc., is capable of traveling through complex pipe networks from 8 to 12 in internal diameter (Ref. 2). Three rubber track units pressed against the walls in equilateral configuration propel this device. It is not articulated, but is short enough to negotiate most turns. Numerous other robots, mostly research projects, have been constructed of this type, using either tracks or wheels.

Yet more complex are vehicles that use serpentine motions or “inch-worm” mechanisms for propulsion. These have shown promise but remain experimental. A project by North Carolina State University uses pneumatic mechanisms at either end of the robot to grip the walls of the pipe, while an expanding center section produces motion in stages (Ref. 3). A “robot snake” by the Institute for Autonomous Intelligent Systems uses a sinusoidal motion and a large number of wheels along its length to propel itself in an extremely flexible way. (Ref. 4)

Purpose of the Project

This project is intended to produce a robot capable of traveling through a network of pipes for the purpose of inspection from inside.

Overview of This Report

Methods employed by the Pipe Crawler team are described in section II: Design Approach; further subdivisions are restricted to the design of each subsystem. The fruit of these efforts is included in section III: Results, which contains a description of the mechanical and electrical systems of the robot, as well as an overview of the final implementation.

II. Design Approach

As the Crawler is somewhat closer to a research project than a design for a commercial product (although such an application should not be ignored completely), there are few well-known solutions to be made use of; even worse, the dynamics of this robot are too complex and influenced by too many factors for simplified analyses to be very useful. Therefore, the development of the Crawler embodies an approach to design and implementation which emphasizes experiment and rapid construction of models to determine the success of new ideas in meeting the project criteria.

These goals are explicitly defined: first, the robot should be a general platform for traveling into a pipe network and returning along the same route, capable of mobility in horizontal and vertical sections of pipe, and stable in either without applying power. It should also be able to negotiate certain pipe fittings, especially elbows of various angles (commonly 90 and 45 degrees). Due to the availability and widespread use of 6 in. diameter PVC sewer and drainage pipe, the Crawler will be designed to accommodate this environment. A human user at the entrance of the fluid system should be able to remotely control the robot using a base device that provides some interface. This can be connected to the robot via a tether, which carries power, bi-directional communications, and a structural cable for extracting the Crawler in case of mechanical failure, all designed with aim of supporting a 100 foot range. Tele-operation is aided by a video camera at the front of the robot and a navigation system that can track progress through the pipe-network and present this information to the user in the form of a constantly updated map on a computer screen. Finally, the Crawler should provide some measure of future expandability, especially the ability to add payloads such as sensors for testing the integrity of pipe walls.

Mechanical and Structural Design

Three mobility requirements can be defined from the goals above: first, the robot must be able to move forward and backward (since it will have to travel back to the entrance without the rather difficult challenge of turning around inside). Second, a capability for travel in vertical pipe sections is necessary; as part of this, it is best for the robot to be statically stable or able to maintain position in a vertical pipe without the use of motors or other powered devices. Third, the robot should be able to move through turns such as elbow fittings.

Many possibilities exist for a solution to the first condition above; therefore it is little help in constraining the design. More difficult to solve is the second requirement, that of vertical travel. Putting aside complicated and unreliable solutions such as rockets or fluid propulsion, the robot cannot move without exerting a force against the pipe walls. Further neglecting exotic possibilities such as vacuum suction (defeated by rough pipe surfaces) or electromagnets (only successful in iron pipes), any such robot traveling in a vertical pipe has to rely strictly on mechanical friction against the pipe walls to maintain its position. Since friction only exists when a normal force is applied to the surfaces, and gravity will not help in a vertical section, the robot has to push against opposing walls of the pipe.

Fig. 2-1. Early attempt at guide wheels using angled wheel mounts actuated by one large compression spring.

One method of doing so is to force wheels or tractor-tread devices outward using springs or other devices; an early experimental model is shown in fig. 2-1. The optimal, exactly constrained version of this design consists of three contact points in an equilateral configuration. Such wheels or tracks, if freewheeling, could guide the robot along the pipe. If driven by motors, these could provide forward propulsion as well. However, the vehicle must be able to travel around curves; in this case, the wheels along the outside of the turn must travel further than the inner wheels, necessitating a differential mechanism, which does not exist for the cylindrical three-dimensional case. Therefore, each wheel (or track) will have to be independently driven and the ratio between wheel speeds electronically controlled.

This scheme does not achieve the ideal of functional independence, however. Forward drive and guidance are now achieved using the same system, necessitating greater operator involvement; furthermore, a system consisting of three driven wheels each with its own motor and drivetrain is needlessly complex. An alternative design would separate the functions of drive and guidance. Using the same equilateral configuration of free-spinning wheels for guidance, it is necessary only to provide a forward force, desirably in some way that does not interfere with that guidance. One such method is a "screw drive" using a rotor to which are attached three (or any integer greater than one) freely spinning wheels forced against the sides of the pipe by springs. Suppose that a motor drives the rotor itself, and that the individual wheels have been displaced by some small angle from the plane of the rotor. This mechanism, illustrated in the figure below, is analogous to a large screw being turned inside the pipe and consequently moving forward.

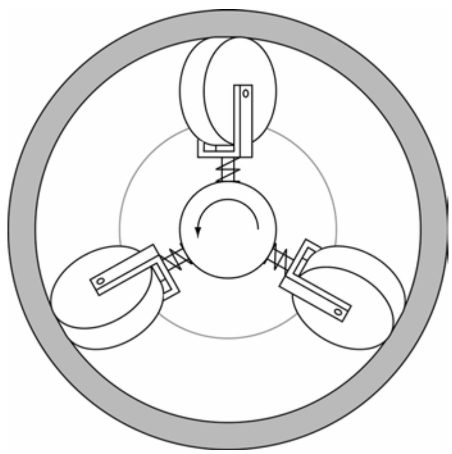


Fig. 2-2. Screw drive concept.

A kinematic analysis can yield insight into the performance of such a screw drive. Each wheel is displaced from the plane of rotation of the screw rotor by some angle θ. Over one revolution of the rotor, each wheel will travel along the inside of the pipe by a length equal to the circumference of that circle, or $2\pi R$, where R is the radius of the pipe interior. Therefore, the screw drive will move forward each revolution by a distance given by:

$$D = 2\pi R \tan\theta \qquad \text{Eq. 2-1.}$$

Forward velocity of the screw drive is determined simply by multiplying this distance by the number of revolutions per minute of the rotor:

$$v = 2\pi RN \tan\theta \qquad \text{Eq. 2-2.}$$

Obviously, greater forward speed is available simply by increasing θ. However, this will also increase the torque required of the drive motor. That presents the option of adjusting the pitch of the screw wheels to act as a sort of variable gearbox, increasing the speed or decreasing the load as necessary for the selected motor and the specific operating conditions. It is possible to derive an expression for the torque required to turn the rotor, but in the absence of manufacturer data for the tire's coefficient of friction, this analysis would not be valuable. An experiment can be conducted to measure the torque requirement directly, which would necessitate the construction of a screw drive rotor.

A simple wooden model, using rubber wheels from LEGO toys, was built and mounted on a length of threaded rod with a handle or moment arm at the end. This arrangement was inserted into a piece of PVC pipe such that the end of the rod with the handle attached protruded from the entrance. A spring scale was used to apply a known force onto this arm; while the experimenter slowly increases the amount of force, the scale is observed and the measurement in pounds recorded at the moment when the screw drive begins to turn. This weight, multiplied by the length of the moment arm, yields the torque required to turn the screw drive. In this case, the measured force of 3.5 pounds, multiplied by the 2 inch handle, gives a torque of 7 in. $\times$ lbs.

It is necessary, of course, to treat such a result with caution; there are many circumstances which could increase the resistance of the screw drive dramatically. As such, it is advisable to select a motor with an ideal running torque (that is, the point in the speed-torque curve which gives the greatest efficiency) somewhat greater than the torque measured above, to allow for the effect of the load contributed by the rest of the robot, and to ensure that the stall torque (typically several times greater than the ideal torque) would remain higher than any resistance encountered in operation.

One final difficulty is presented by the screw drive: as the wheels extend to the wall of the pipe itself, it is impossible for anything which does not rotate to pass around it. Electrical wiring which has to extend from end to end of the robot cannot simply be routed around the hub as with guide wheels - the piston units would catch that wire and destroy it. Furthermore, it is desirable to pass some structural, non-rotating member to both sides of the screw drive, so that the entire robot is not made to rotate. The only solution is to make provisions for passing through the center what cannot go around. Practically, this means that the screw hub must rotate on a hollow shaft and that this shaft must have a large enough diameter to accommodate the wiring. Worse yet, since hollow-shaft motors or gearboxes are very rare (usually custom-made for specialized applications), it is necessary to drive the hub by gears or pulleys attached to a motor that is somewhat offset from the center.

As mentioned above, the third condition for complete mobility in the pipe environment is the ability to travel around bends or elbow fittings. Fulfilling this criterion necessitates a short vehicle; the ends of a longer robot will collide with the walls of the pipe when the turn is attempted. However, such a restriction does not leave enough room for the payload, microcontroller, video camera, motors, and other systems required by the robot. For this reason, it is better to design a robot in several sections, with flexible articulations in between. Such an arrangement can be as long as needed to accommodate any electrical systems or other components, provided that each segment is small enough to travel through the tightest elbow.

Obviously, this linkage should be flexible enough to allow the segments to traverse the elbow; however, experiments reveal that some methods of articulation are too flexible, causing the robot to buckle when pushed from behind. In practice this will occur with segments which lead the front propulsion unit, where front is defined according to the direction in which the robot is traveling. If the force contributed by both screw drives is not exactly equal, sections in between may also be affected. Any such instability will result in guide wheel hubs which are not parallel with the pipe - a dangerous situation that can cause the wheels to jam and, consequently, the motor to stall.

The first attempt at optimizing the flexibility of a linkage is seen in fig. 2-1 above; here, three segments are joined with lengths of clear vinyl hose. This proved unsatisfactory, as the hose was slightly too stiff, and, furthermore, had acquired an inherent curvature as it had been coiled on a roll during storage. Consequently, the curved hose forced the segments to buckle, while simultaneously being too stiff to pass the elbow! A second model provided the solution: very flexible universal joints can be bent to extreme angles to allow passage through the bend, while an arrangement of springs can be used to stiffen the joint, preventing instability. This has the added virtue of being adjustable, as the springs can be tightened further or replaced to experiment with different levels of flexibility.

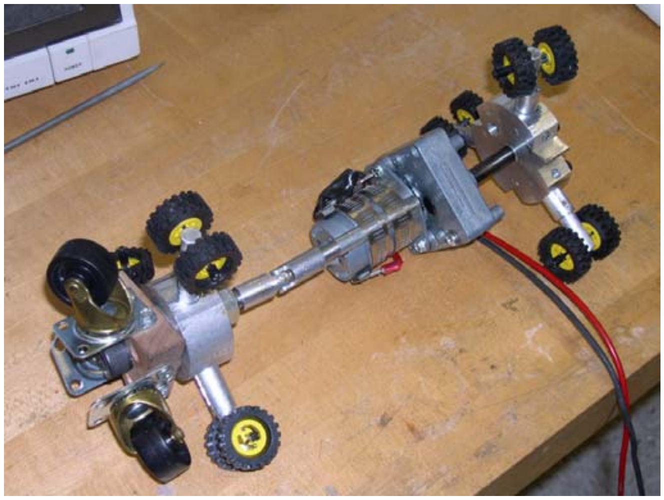


Fig. 2-3. Screw drive powered model.

Figure 2-3 depicts a test model featuring an early screw drive, one set of guide wheels, and the flexible linkage without stiffening springs (this model revealed the need for them). An important addition to this version is the triangular arrangement of caster wheels mounted at the front. This is designed to have a smaller total diameter than the guide wheels, and thus serve as a sort of transition into bends. It was observed that the caster wheels do not actually rotate during use, but, being composed of very hard plastic, merely slide against the walls of the pipe. It is therefore simpler to outfit the front (and rear - since the robot is designed to travel in both directions) with a plastic dome or ring of similar diameter.

Navigation System

One of the innovative features of the Pipe Crawler is the ability to trace its movements inside a pipe, thus creating a map of the pipe's layout. In general, to fix an object's position in space (and the history of this position, if recorded with sufficient frequency, constitutes a map of the route traveled), the motion of the object along three orthogonal axes, X, Y and Z should be measured. However, common methods for doing this (except for GPS and other systems which make use of external references, rejected here for reasons of cost, size, power consumption, insufficient resolution, and possible inability to penetrate ground or certain type of pipe walls) are mounted on the vehicle itself and thus determine displacements with respect to the current orientation (neglecting the possibility of gyroscopically stabilized gimbal mounts, which are far too bulky and complex for this application). Therefore, in order to use three linear displacement measurements to track position, it is necessary also to determine the orientation of the object, so that future movements along the three unfixed position axes can be correctly interpreted with respect to some absolute coordinate system (defined most conveniently at the entrance of the pipe network). Orientation must also be measured with respect to three orthogonal axes; it is simplest to do so about the three linear displacement axes X, Y, and Z, in which case the resulting angular deflections are commonly called pitch, yaw, and roll.

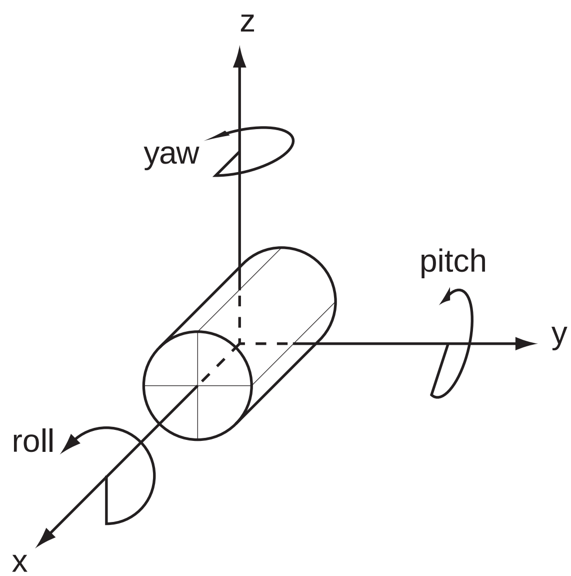


Fig. 2-4. Definition of axes for inertial navigation.

One way of measuring changes in position and orientation is inertial navigation, most commonly using three accelerometers for the three axes of linear motion, and three gyroscopes for the three axes of angular displacement. Unfortunately, accelerometers present several problems that complicate their use. First, accelerometers measure acceleration, so they can be affected by gravity. Accelerometers of a certain type (the most common, lowest cost, and most compact type) will read 1 g if oriented normal to the earth's surface. Therefore, the range of additional acceleration, resulting from the motion of the device, that can be measured is limited; this effect also complicates the interpretation of the data, making it necessary to track the "down" direction and subtract the effect of gravity vectorially from accelerations along each of the three axes.

Second, using acceleration measurements to determine displacement requires a double integration, not a terrible burden computationally, but liable to produce inaccurate results if sampling rates are low (and, as is seen later, they will be). Consider the hypothetical plots of displacement, velocity, and acceleration in fig. 2-4. In this simple constant velocity case, it is easy enough to sample the displacement (provided that such a sensor exists), as this signal contains only low frequency components. Reproducing the velocity plot requires a higher sampling frequency, as any discontinuity will produce harmonics at infinite frequencies. The still sharper plot of acceleration, represented by two impulses in this idealized example, is also theoretically impossible to capture exactly; practically, it will require a still higher sampling rate to provide acceptable results. For these reasons, it was decided, after some initial experiments, to abandon the use of accelerometers in this project.

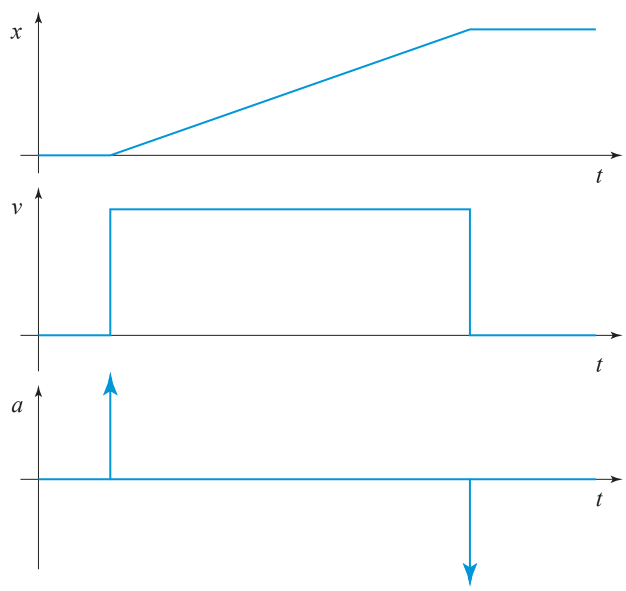


Fig. 2-5. The relationship between displacement, velocity, and acceleration.

Furthermore, the unusual environment of the pipe network makes a simpler scheme possible. Since the robot travels through the pipe like a train travels on rails, there is no possibility for the robot to move along axes orthogonal to its longitudinal axis. Therefore, if the vehicle's linear displacement along this axis is recorded, together with any changes in orientation that occur when bends or other fittings are encountered, a map could be drawn of the path the vehicle has followed. Therefore the six degrees of freedom to be tracked in the general case is reduced to only four degrees of freedom, three of angular displacement, to be measured by gyroscopes, and one of linear displacement with respect to the long axis of the pipe – and this can even be determined using direct methods such as wheel odometry or measurement of the length of the deployed tether.

The most practical method is the use of an optical encoder on the robot itself, turned by one of the guide wheels and consisting of either an IR emitter/phototransistor pair with a slotted disc, or an IR photoreflector aimed at a disk colored with strips of different reflectivity. Because of the design of the Pipe Crawler's wheels, it is easiest to mount an IR photoreflector directly on the wheel mount. First, a disc with an alternating pattern of black and white "pie slices" is attached to the wheel. With the photoreflector placed a few millimeters away from the disc, its output signal goes high when opposite a light colored segment and low when observing a dark segment. When the wheel is spinning, the signal is compose of a series of pulses that can be counted to determine the number of wheel rotations, and, subsequently, the distance traveled.

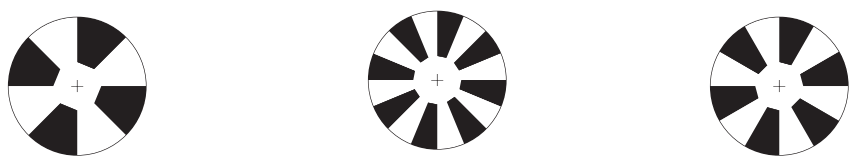


Fig. 2-6. Photoreflector disk patterns of different resolutions.

Several types and models of electronic gyroscopes were investigated, but most were either too large or too expensive for this application. Only one class of devices, the recently developed IMEMS (Integrated Micro Electro-Mechanical System) gyroscopes made by Analog Devices, Inc., were small, affordable, and accurate enough (Ref. 5). These devices are simple to use and interface with, as Analog Devices employs a new micro-machining technology that allows a functionally complete angular rate sensor, with all of the required electronics, to fit on a single 20-pin dual-inline-package device (indeed, the gyroscope itself is available in an even smaller surface mount device, about the size of a watch battery, but the DIP package was selected so that it could be easily interfaced to). The gyroscope's output signal is a voltage proportional to the angular rate about the axis normal to the top surface of the chip. When connected to an analog-to-digital converter, the instantaneous angular rate of each gyro can be sampled and recorded by a computer; a numerical integration of this data will results in the angular displacement. Sample all three gyros, where one is positioned to read each of pitch, yaw, and roll displacements, and the robot's orientation in three dimensions can be tracked.

Microcontroller and Data Communications

In order to acquire data from the navigation system sensors and transmit this to a personal computer at the entrance of the pipe for processing and display, it is necessary to include a small microcontroller or other computer on-board the robot. This would have to accomplish the A/D conversion of the sensor voltages, count the pulses at the photoreflector output, and provide some mechanism for communications over a wire or set of wires, preferably with a minimum of external hardware. Due to the previous experience of team members with Motorola microprocessors, specifically the many variants of 68000 and the later HC11/HC12, a Motorola MC9S12DP256 single-board computer was selected. The DP256, one of Motorola's newest models, is very capable and well suited for this application: it features 16 channels of 10-bit A/D conversion, four 8-bit pulse accumulators (useful for counting photoreflector pulses without the need for high-speed polling of conventional inputs), two full-duplex asynchronous serial communication modules, eight 8-bit pulse width modulated outputs, on-board EEPROM, several general purpose I/O ports, and more.

Pre-manufactured printed circuit boards are available from several manufacturers that house the DP256 chip, a voltage regulator, and header pins for easy access to all of the microcontroller ports. Some also provide additional RAM and other electronics to augment the capabilities of the microcontroller, or integral breadboards for prototyping and experiments. Although such a product proved useful during the development of software for the Pipe Crawler, the space constraints of this robot make larger, more complex boards impossible. Instead, a suitable single-board computer was found in the EVBplus MiniDRAGON (Ref. 6). This is an economical and extremely compact (2.2 in. by 3.2 in., almost exactly the size of a credit card!) HC12 product, which features a RJ-12 plug like that used in telephone handsets for interface with the serial port of any PC.

Aside from its usefulness in data acquisition and transmission, the on-board microcontroller is quite necessary for receiving control signals from the operator and powering the appropriate drive motors. Unfortunately, DC motors require quite high power to function properly, but microcontroller I/O ports are only capable of power levels appropriate to logic circuits. Therefore, an additional circuit is needed which will interface with the microcontroller while providing the necessary power to run the motors. One possible and much used design, called an H-bridge, is made up of four high-power transistors with the motor connected between them, in a configuration that resembles a capital H.

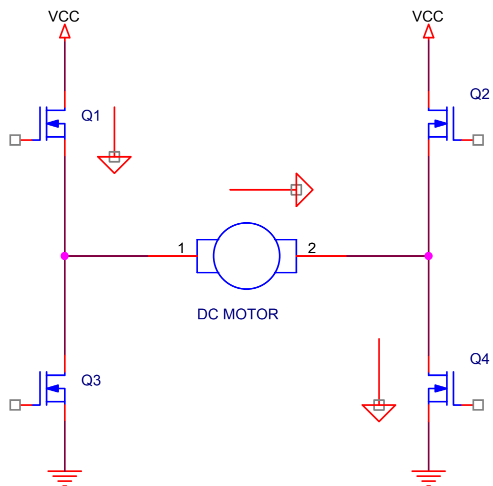


Fig. 2-7. H-bridge circuit.

When transistors Q1 and Q4 in Fig. 2-1 are turned on, by receiving logic high voltage at their gate inputs, current will flow through the motor as indicated by the arrows, causing it to turn. The DC motor can also be made to run in the opposite direction by merely turning off Q1 and Q4, and turning on Q2 and Q3 - the reverse direction is the only reason for four rather than two transistors.

One disadvantage of this kind of H-bridge is that, since the MOSFETs are capable of high power, the microcontroller signal must also be relatively powerful (although not as powerful as would be needed to run the motor directly) in order to turn on the transistors; otherwise, it will be necessary to employ a more complex circuit. Also, DC motors, being high inductance loads, can potentially create harmful high-magnitude voltages when they are abruptly switched off, necessitating protection diodes in the circuit.

The best way and simplest way to avoid these problems is to use an IC H-bridge which integrates the more complex H-bridge circuit (diode protected and capable of driving large motors while accepting only logic-level inputs) into a single compact package. The IC H-bridge has both kinds of needed inputs, power inputs and logic inputs, integrated in a single package.

The required inputs are a direction control signal of logic low or high, and a PWM signal, which contains information about the desired speed of the motors. Both signals are created by the microcontroller, in response to control instructions received through its serial communications interface with the user PC.

The on-board Pulse Width Modulation module on the MC9S12DP256 microcontroller is a sophisticated system comprised of user-programmable registers that control the characteristics of the output PWM signal, such as period and duty-cycle, and the enabling of its formation by the module's hardware. A PWM signal is basically a periodic square wave that alternates between logic high and logic low voltage levels. Gradations in motor speed are achieved by varying the length of the logic high portion of the signal as a percentage of the total period, called the duty cycle, so that the motor receives varying average voltage levels, causing it to spin slower or faster, as the case may be. This feat is, to a large degree, not possible using relays, due to their slow activation and deactivation times, or potentiometers that yield a varying DC voltage, due to the necessity of a full strength voltage, albeit pulsed, at the motor coils to produce constant shaft torque.

The serial communications module on the Motorola DP256 chip is designed to create RS-232-compatible serial signals, allowing it to communicate with any computer system that includes an RS-232 port. Data baud rates, as well as byte length (8 or 9 bits per byte) and parity (even, odd, or none), are controlled by the hardware, and can be set and reset in the user program, providing flexibility and adaptability in the design.

Video Camera

It is necessary for the Pipe Crawler to provide the user with a visual assessment of its surroundings, for two reasons: first, so that the robot can be correctly navigated through the pipe by the distant operator; second, to allow inspection of pipe integrity, fouling, or other problems in the plumbing network. Since no natural source of light is available, an artificial one should be provided, or the selected video camera should be able to see in very low light conditions. In order to examine details of the surrounding pipe, it should be able to resolve details as close as one inch; however, the camera must also see two to three feet clearly for navigation purposes.

Since color is not of significant importance inside a pipe (and it is easy enough to upgrade the robot should more funds become available) it was decided to use a monochromatic camera. The MPJA Company offers a black and white video camera with a 1/3 inch CCD on a single circuit board; this camera is sensitive in the infrared frequencies and is conveniently available with already mounted infrared LEDS for illumination (Ref. 7). Although no visible light is produced, this camera is capable of illuminating and capturing details 20 to 30 feet away in otherwise perfect darkness. Furthermore, the focus is easily adjustable with a set screw; some experiments revealed that text 1 inch away could easily be read while images at several feet remained quite clear.

Transmission techniques were evaluated to find a camera that will allow the user to receive near-real-time video. Since a tether is being used to transmit power and serial communication for the robot, it might also be used to carry a video signal. While it is theoretically possible to capture the video using the microcontroller and transmit the data over the serial link, such a possibility must be rejected as the volume of information transmitted for navigation purposes is already close to overwhelming the capabilities of this channel. It is very much easier to include a thin cable in the tether bundle and use this to carry NTSC video directly. A very flexible coaxial cable was found and tested over a 100 ft. length; this was deemed suitable because it showed no appreciable signal degradation at all.

Power Supply and Distribution

Power requirements cannot be estimated until the mechanical design of the robot is almost complete, so that the loads on the motors and their consequent current draw are known. It is also necessary to select the microprocessor, video camera, and motor driver circuits so that the power used by each is determined. For this reason, the design of the pipe crawler's power system was left loosely defined until relatively late in development.

Power consumption of each device in the Pipe Crawler is obtained from their respective specification sheets. Since no specifications for the motor is available, an idle and stall current was measured using a power supply and an ammeter. The required information is gathered and the power consumption of the robot is calculated in Table 2-1

Device	Nominal voltage	Nominal current	Nominal power	Peak current	Peak power
Microcontroller	8 V	40 mA	320 mW	300 mA	2.4 W
Gyroscope and Optical Encoder	5 V	50 µA	250 µW	50 mA	250 mW
Motors and H-bridges	12 V	1 A	12 W	1.8 A	21.6 W
Camera	12 V	200 mA	2.4 W	200 mA	2.4 W
Total Power Consumption:			14.72 W		26.65 W

Table 2-1 Power consumption of on-board devices (peak voltage is the same as nominal voltage).

Tether diameter and weight should be kept to a minimum to reduce the physical load on the robot. For this reason some voltage drop across the power cable is considered acceptable so that a smaller gauge wire can be used. Since 12 volts DC is the highest voltage that is required to operate the Pipe Crawler, 12 volts will be sent on the tether, and other voltages obtained by using regulator circuits to produce 8 and 5 volts. The DC motors can operate across a considerable range of voltages; therefore it is more efficient to avoid regulating power to the motors by running them on the main tether power directly. To calculate the maximum input power required by the regulators, it is necessary to consider their efficiency:

$$P_{in} = P_{out} / Efficiency[\%] \qquad \text{Eq. 2-3.}$$

By adding P_{in} to the power consumed by the motors and H-bridges, the total amount of power needed by the robot is 31.31W. As mentioned above, the gauge of the power cable should be kept as high (keeping in mind that higher wire gauges indicate smaller diameter wire) as possible. However, this will entail a larger voltage drop over the length of the tether, necessitating a higher voltage power supply to ensure that the robot receives 12 volts. A 15 volt, 6 amp supply was found and outfitted with a case, switch, indicator light, and fuses (fig. 2-8).

Fig. 2-8. Power supply.

Resistance per thousand feet of wire is given by:

$$(\Omega / Kft) = (\%VD * V_s)/(0.2Id) \qquad \text{Eq. 2-4.}$$

Where *%VD* is the desired percent voltage drop, V_s the supply voltage, *I* the current over the line, and *d* the distance from supply to load. Using this equation, and the wire gauge sizes specified by the National Electrical Code, as quoted by Messenger and Ventre (Ref. 9), a 16 gauge wire is sufficient to carry this power, while remaining flexible enough to avoid impeding the physical progress of the robot.

User Interface

As mentioned above, it is necessary to provide some device that can accept control inputs from the operator and transmit these via the serial link to the on-board microcontroller. Further, it must simultaneously receive sensor signals from the robot, interpreting and presenting them in visual form (and storing this information for later retrieval). The simplest way to achieve this combination of serial communications, graphical display, data storage, and ability to accept user inputs is obviously the personal computer, equipped with suitable software.

Some methods of programming such an application were considered. Numerous data acquisition packages exist and are widely used in the scientific and engineering communities. Furthermore, it is always possible to use full-featured programming languages on a lower level to accomplish the desired goals, purchasing power and flexibility at the expense of ease of use. First investigated in this category was the possibility of writing the application in pure C/C++, to run in the UNIX environment and making use of the X Window system to provide a graphical interface. This was deemed to be needlessly complex, as displaying any graphics at all with such a technique requires the creation of very low-level plotting routines that directly write bytes to a buffer in memory; plotting three-dimensional vectors is even worse, as this necessitates writing higher-level functions for projecting points in 3-space onto a viewing plane.

Matlab was considered and rejected as its serial communications capabilities, a recent addition, are not especially mature at this time. Labview is, of course, made for data acquisition, but both it and Matlab suffer from their lack of a complete, rigorous programming language, as such features have evolved rather piecemeal in Matlab and are burdened by an unnecessary and often counter-intuitive visual programming environment in Labview; additionally, the cost of either program is prohibitive.

Perl, an interpreted programming language widely used with Unix systems (although available for other platforms as well), can answer many of these complaints. Most often employed in text processing or web site applications, it is nonetheless possible, and indeed relatively easy, to construct graphical, event-driven interfaces when certain additional modular extensions to Perl are made use of. One of these modules, the PDL or Perl Data Language, offers mathematical functions, highly optimized manipulations of matrix data, and three-dimensional plotting capabilities (along with all of the buttons, scroll bars, and other amenities of the GUI) much like those of Matlab, with the power and flexibility of C or other lower-level languages (Ref. 10).

III. Results

Mechanical Construction

The final robot employs seven articulated segments: two units providing propulsion, one carrying the payload, two ‘heads’ or leading units (the nose and tail of the robot are similar to each other to allow bi-directional travel), and two extra wheeled sections used to guide the payload and prevent it colliding with the walls of the pipe. The figure below illustrates the arrangement of these segments (so that the mechanical and structural components can be seen clearly, this picture depicts the robot lacking most of the wiring and electronics that would be added later).

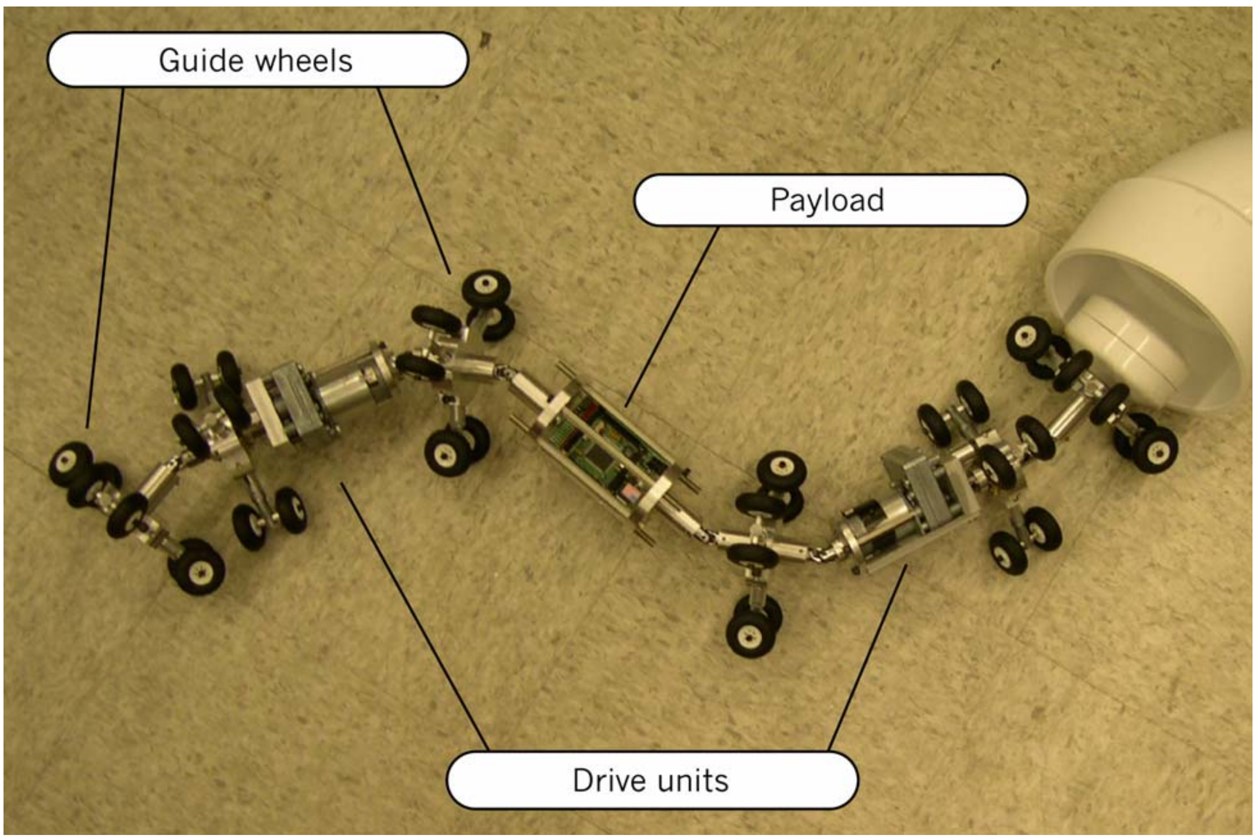


Fig. 3-1. Final robot, showing seven articulated segments.

All of the wheels, whether used as guides or as part of the screw drives, are mounted in pairs to the same piston devices, and these in turn are inserted in identical circular hubs and secured with set screws - this providing the option of rotating the piston cylinder to achieve different pitch angles in the case of the screw drive. Each piston unit consists of a hollow aluminum tube, slotted to accept a pin in order to prevent rotation of the inner steel piston, which is drilled at one end so that a standoff, like those used to mount circuit boards, can be press-fit into the rod. These standoffs are available with a 6-32 UNC thread through both ends. The wheels themselves are model aircraft tail wheels, 1.5 inches in diameter and consisting of a solid rubber tire around a plastic hub; these ride on the unthreaded shoulder of 6-32 cap-head bolts which are screwed into both ends of the standoff and further secured using a nut and lock-washer. Fig. 3-2 provides a detailed, dimensioned view of this assembly.

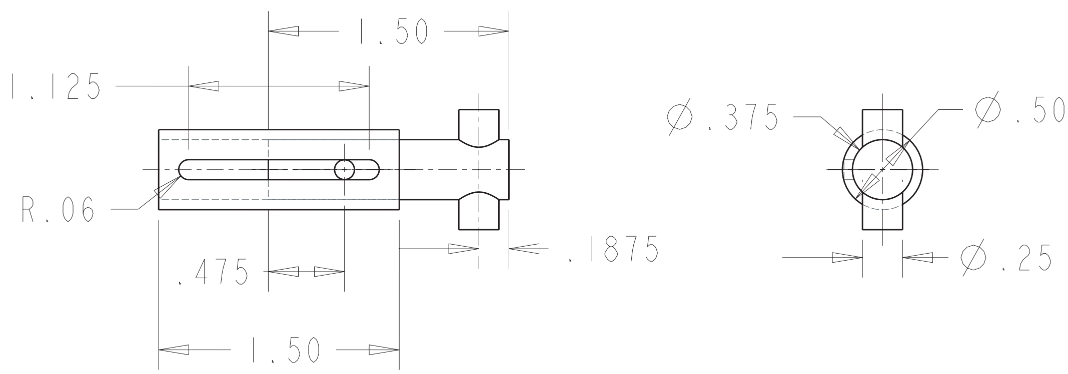


Fig. 3-2. Drawing of wheel unit assembly.

Three such piston devices and their attendant wheels are included in each hub assembly, a photograph of which is provided in fig. 3-3 (this image depicts a guide wheel arrangement specifically, although the drive units use identical hubs with the piston cylinders turned by some angle). Barely visible through the guide slots are the springs which force the wheels outward against the walls of the pipe. Also apparent are holes (tapped for a 10-32 thread) which accept set screws for two purposes: a set screw passes through the face of each notch to engage the wheel piston, and another set of three tapped holes are located radially to attach the entire hub to whatever is in the center - in the case of guide wheels, an aluminum cylinder that serves as a "backbone" and a connection to the articulations of the leading and following segments.

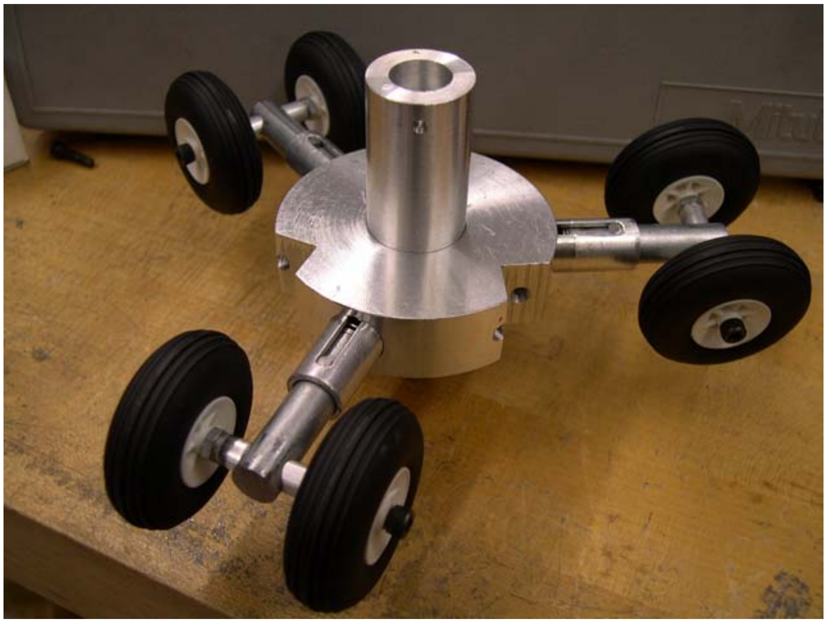


Fig. 3-3. Assembly of hub and wheel units.

Both drive units make use of assemblies identical to the one in fig. 3-3, with one exception: inserted in the center instead of the cylinder seen above is a stepped hollow shaft with two ball bearings and three stop collars intended to transfer thrust loads from the wheel hub through the bearings and into the shaft, which is itself rigidly attached to the body of the robot. A large brass ring gear is attached to the face of each drive hub using three 1/16 in. pins and three 4-40 thread screws each. This assembly, including the shaft and the recessed ball bearing (both light press-fits of approximately 0.001 in. interference, or, in other words, the inner part has an outer diameter 0.001 in. larger than the inner diameter of the outer part) is depicted in fig. 3-4.

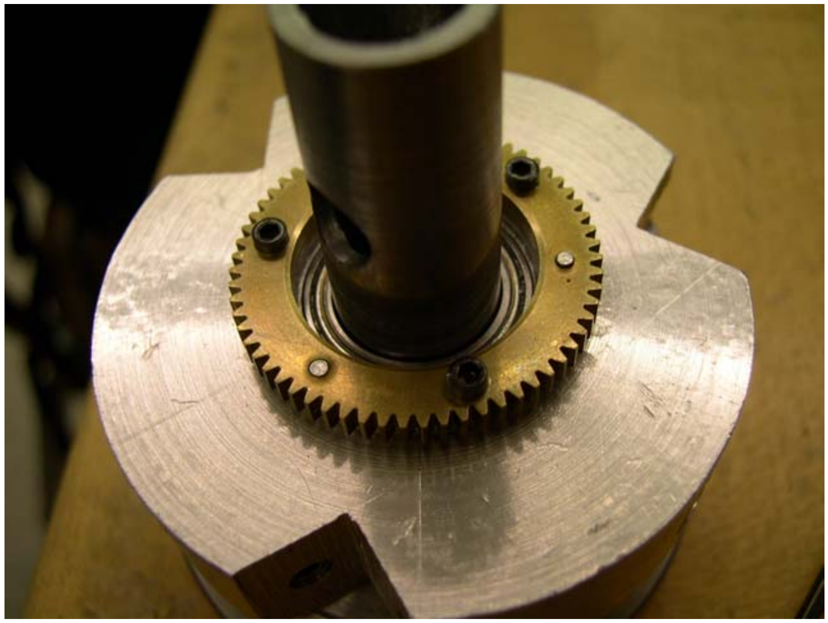
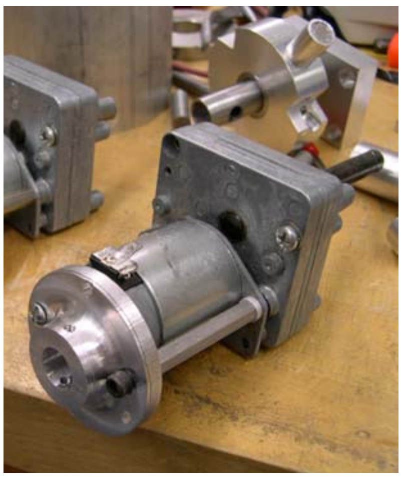


Fig. 3-4. Drive hub with gear, shaft, and bearing.

One end of this shaft is bored to accept the articulation to the next section; the other end is press-fit (in this case, as there are no delicate bearings to consider, a much firmer interference fit of 0.005 in. was specified) into a plate designed to bolt onto the gearbox of the drive motor. This motor powers the ring gear of the hub through a small spur gear; as the gear is only slightly larger than the motor shaft itself, some difficulty was encountered in manufacturing an coupling between the two. Fig. 3-5 depicts the final design: two 1/16 in. pins through the face of the gear prevent shear between it and the aluminum adapter behind it, which is drilled at the opposite end to accept the shaft. A large countersunk screw prevents vibrations or axial forces from separating the gear and adapter during operation.

Fig. 3-5. Spur gear adapter.

It is also necessary to provide a means to connect the next segment of the robot to the back end of the drive unit. Unfortunately, due to the complex geometry of the back of the motor, there are no easy methods by which a plate or other extension can be attached here. The final solution involves removing one of the bolts which holds the motor itself together and substituting for this a somewhat longer bolt, so that a circular articulation mount can be held against the motor at this one point, as seen in fig. 3-6a.



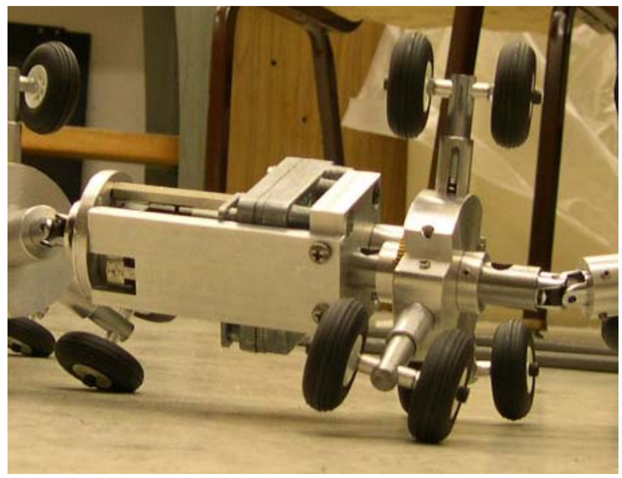


Fig. 3-6a and b. Drive motors featuring rear mount point for articulation.

To provide additional support, one of the screws which holds the motor to the gearbox is removed, and a long standoff put in its place; finally, to prevent excess torsion (included that generated by the motor itself) from damaging the motor, a rectangular plate is attached underneath the drive unit between the gearbox mounting plate and the rear articulation mount, to provide it with a third attachment point and to stiffen the whole assembly torsionally (fig. 3-6b).

Most development models had used articulations consisting of high-quality universal joints. As six are employed in the final robot, however, it is desirable to reduce costs here, if possible. Universal joints intended for power-transmission applications are capable of speeds and torques far in excess of what can be expected in this application, where all that is necessary is a sort of two-axis hinge. The least expensive implementation of such a coupler can be found in an ordinary socket wrench universal joint, intended for flexible tightening of bolts. A 9 mm hex socket u-joint sold under the Craftsman brand by Sears was found to be of ideal dimensions.

Fig. 3-7. Articulation, featuring universal joint and stiffening springs.

Revealed in the above figure is the universal joint, slid into both segments and held there with set screws. Also apparent are three bolts, drilled at the ends to accept tension springs and secured with nuts. The other end of the spring hooks into a plate with three holes at the outside circumference. Other articulations are much the same, with the possible use of bolts on both sides to connect the three stiffening springs.

As discussed above, to achieve mobility through pipe elbows it is necessary to provide some gentle transition by means of a smooth dome or ring at the ends of the robot. Such a structure can also be made to house the video camera, at the front, and tether connections, at the rear. Each was constructed from two PVC end-caps that were cut short and joined by a short length of pipe. In the case of the video camera (fig. 3-8), a large hole was cut in the center of one of these end-caps and a clear plastic dome inserted, to allow a view out of the front of the robot.

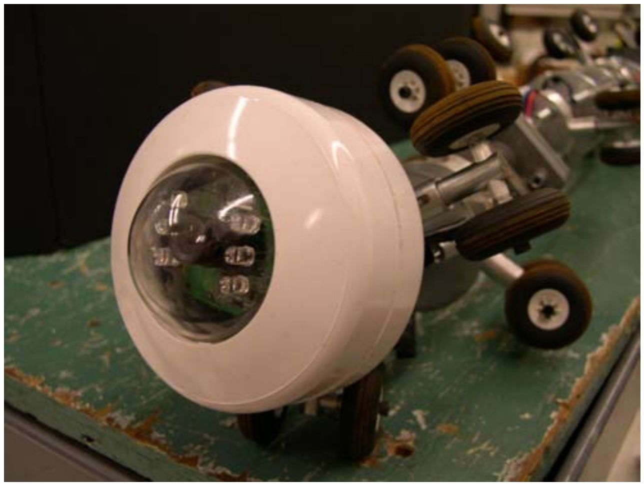


Fig. 3-8. Video camera and transition section.

Finally, the microprocessor and other electrical components, which comprise the payload of the vehicle, must be provided with mounting locations and a means by which they can be protected against impacts. For this purpose, the centermost section of the robot is a hexagonal cage, as hollow as possible to accept electronics inside while still structurally able to serve as part of the "backbone" of the machine. This was constructed from two aluminum plates, serving as end-caps, and six sturdy electronics standoffs between them, as shown in fig. 3-9. The protruding ends of the standoffs were drilled to serve as spring mounts for this section.

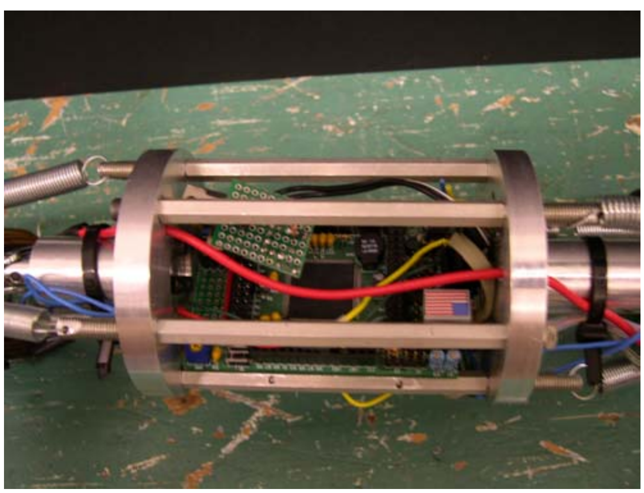


Fig. 3-9. Payload cage, showing spring mounts and electronic components.

Electrical Systems

Two DC motors drive the Pipe Crawler through the pipe. Each one requires 12 volts and draws varying amounts of current, depending on load; the greater the torque acting against it, the greater the current required. In an unloaded state, they draw 400 milliamps each; stall or maximum current is approximately 1.5 amps. One driver chip that meets these specifications is the LMD18201 H-bridge, manufactured by National Semiconductor (Ref.). With a maximum voltage rating of 55 volts, and a continuous current rating of 3 amps, one of these has more than enough capability for each DC motor. The two H-bridge chips are physically mounted inside the payload section, underneath the microcontroller, and are bolted to an aluminum plate that serves as a heat sink to improve the power handling capability of the chip (a maximum of 25 watts can be dissipated by the IC, which at 12 volts allows slightly over 2 A to flow through the motor).

Testing of the H-bridges revealed 1 kilohertz to be an appropriate frequency for the PWM switching that controls the motor speed. Longer periods were evaluated and found to disrupt the smoothness of the motor operation, especially at lower duty cycles; because of certain requirements found in the LMD18201's specifications, shorter periods would necessitate additional components in an already confined space.

The microcontroller is run by a 16 MHz crystal oscillator; this frequency is divided by two, yielding an 8 MHz clock signal for the CPU. Additional dividers are controlled by software in order to further reduce the 8 MHz to other speeds for use in clocking other internal modules, such as those implementing PWM, A/D, and serial communications. Frequency scaling the main clock by 1/32 (250 KHz) creates the clock input to the PWM; 250 cycles of this are used to define the period (1 ms) of the PWM output signal that controls the motor speed. It is possible then to define the length of the logic high portion of the signal as anywhere from 0 to 250 counts of this clock, but for practical reasons, three speeds have been chosen, represented by 50%, 75% and 100% duty cycles, or 125, 188, and 250 clock cycles, respectively.

Clock speed has also been divided to yield a 2 MHz signal for the A/D, as specified in this module's data sheet. This device is capable of 8, 9, or 10 bit precision. For the purposes of sampling the outputs of the gyroscopes, which can vary from 0 to 5 V DC, 10 bit precision can resolve voltages differing by as little as 4.88 mV. 256 different voltage levels are available with 8 bit precision, yielding a resolution of 19.53 mV, more than acceptable for this application, as it is likely that noise and the inaccuracy of the gyroscopes is of similar magnitude. Selecting 8 bit resolution, and owing to the specified accuracy of the A/D of ± 1 least significant bit, the maximum error in the angular rate (contributed by the digitization) is only ± 1.3 degrees/second, or less than 0.9% error.

Another source of error is the limitation on sampling rates imposed by the baud rate of the serial communications link. This rate, set to 38.4 Kbps, or 38,400 bits per second, is by far the "bottleneck" of the data acquisition system, due to the fact that moving data serially is inherently slower than the exchanges internal to the microcontroller, which benefit from their parallel nature and from being very much shorter. In addition, sending just one data byte made up of 8 bits requires that a total of 10 bits be transmitted because of the inclusion of start and stop bit identifiers. This means that a total of 3840 8-bit data bytes can be sent every second, each one lasting 261 microseconds. The A/D converter, meanwhile, needs 18 of its clock cycles to complete a single conversion, for a total time of only 9 microseconds - it is no help at all to sample at any rate higher than 3831 kHz. Fortunately, the slow progress of the Pipe Crawler makes sudden changes in angular velocity unlikely, and therefore this rate, as verified by experiments, is acceptable.

A freeware program called MiniIDE, for mini-Integrated Development Environment, offered by MGTEK, helped in the testing of the microcontroller and the various peripheral devices it interfaces with (Ref. 11). Several programs, written by the team, were used in testing such operations as A/D conversion of the gyroscopes, collection of photoreflector pulses, and full-duplex communications between microcontroller and host PC. Testing also revealed that serial communication of speeds up to 38.4 kbps over 100 feet is possible using high-quality CAT-5e cable, which exceeds the limits of 20 kbps and 50 feet specified in the RS-232 standard.

The microcontroller contains a program, written by a member of the team, that directs the synthesis of the motor control signals (including the PWM signal), samples the gyroscopes at regular intervals, collects the odometry pulses, and transmits the sensor data to the PC, while receiving and interpreting control instructions. The program consists of a four-part loop, based on the transmission of four data bytes, and utilizes polling routines that check the internal module flags to determine when actions are to be taken and instructions carried out (fig. 3-10).

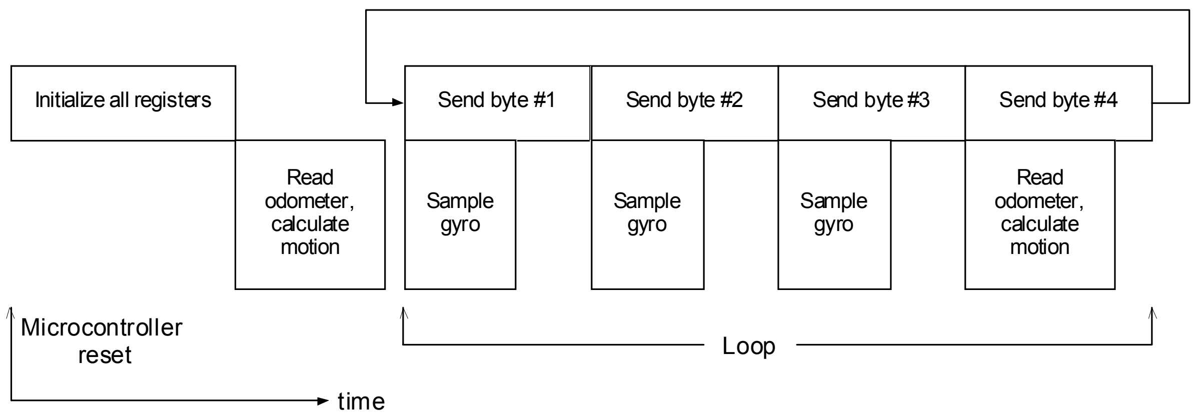


Fig. 3-10. Microcontroller program flow.

As seen in the figure, all register initializations take place initially after power is applied to the microcontroller. Byte 1 consists of a multi-purpose byte made up of the total number of photoreflector pulses counted since it was last sent in bit 0 (this only requires the use of the least significant bit of the byte due to the high speed of transmission, compared to the infrequent pulses from the photoreflector), an identifier consisting of a '1' in bit 7 (this bit, if received out of order, alerts the host computer that a reset of the microcontroller has occurred), and possible error codes to let the user know the status of the robot in bits 1-6 (one of these also indicates a reset condition). Bytes 2 to 4 are the results of the three A/D conversions of the gyroscopes.

The flow of the program, as stated before, is limited by the speed of serial transmission, so, to obtain greater efficiency, other instructions occur while the data bytes are being sent. Each data byte is transferred to the transmission shift register once a flag shows it to be empty of the last byte. At this time, either an A/D conversion is started, or the pulse accumulator register is read and the difference determined. Both of these steps take relatively short times, as can be seen in the figure, and are completed well before the end of the new transmission. Thus, their results are stored in a buffer, and the receiver register flag is polled to verify if a control byte has been received. If one has, then it is copied and compared with a list of used commands until a match is found (the receiver is checked during every byte so no overrun can occur). Then, the particular instructions specified by that command are executed and the program returns to wait for the end of transmission again. The complete loop takes 1.04 milliseconds, therefore each gyroscope is sampled every 1.04 milliseconds, or 960 times per second, and transmitted at the same frequency, giving a time base for the integration that occurs in the host computer.

Overview of Final Implementation

Some photographs of the final Pipe Crawler will indicate the complexity of this device when all components, mechanical and electrical, are assembled. Figure 3-11 depicts all seven segments of the assembled robot, with the tether visible at the left.

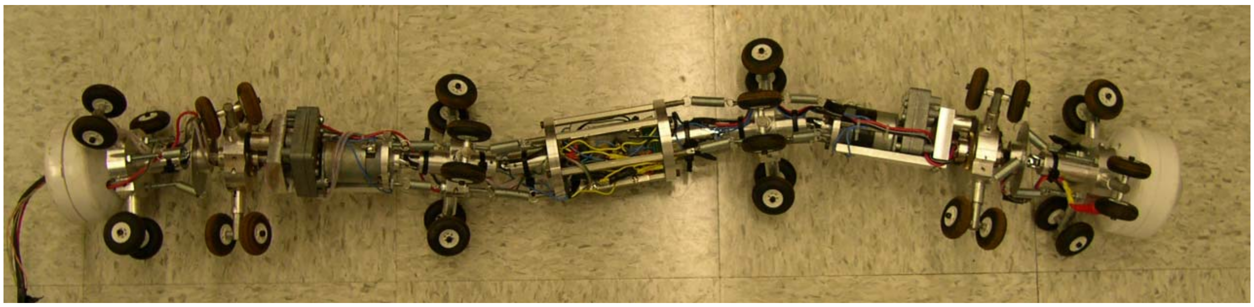


Fig. 3-11. Final Pipe Crawler.

Figure 3-12 illustrates the source of much of the difficulty of this project: the hollow shaft screw drive, with wires passed through the center.

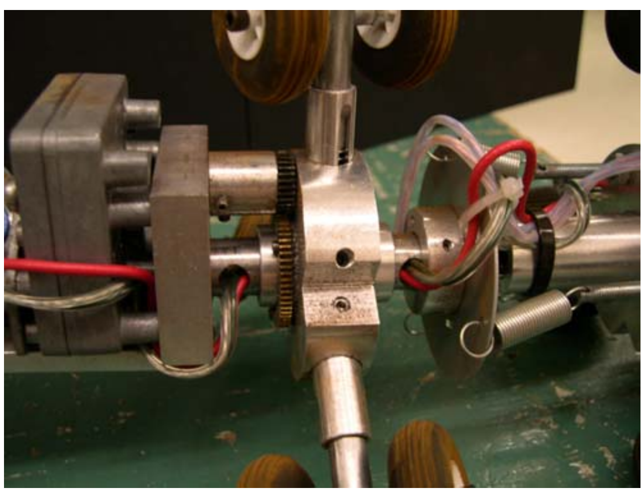


Fig. 3-12. Routing of wires through drive section.

And finally, figure 3-13 shows clearly the rear segment of the robot, with the various components of the tether bundle entering through a rubber grommet.

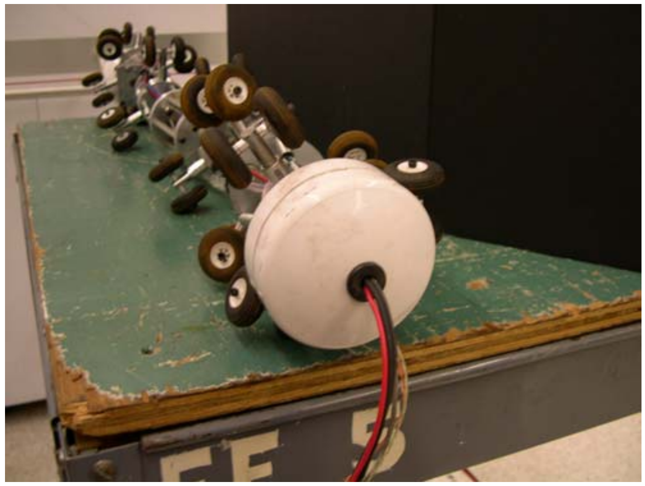


Fig. 3-13. Tether end of robot.

IV. Conclusions

Many of the design goals of the Pipe Crawler project have been completely fulfilled. The novel "screw drive" concept has been proven to work, and the propulsion of the robot has been successfully conducted using only one or two motors, a radical simplification over existing efforts. The guide wheels prevent the rest of the robot from rotating in response to the spinning of the angled wheels. And the electronic features of video transmission, inertial navigation, and microprocessor control of the robot have been implemented and tested with success, at least on the bench.

Unfortunately, the project cannot be considered completely successful as this date as several design goals remain unfulfilled. Some problems were encountered when attempting to navigate the robot through elbows and in vertical sections that were not fully resolved by the time of the demonstration in the team's final presentation. Although the robot was able to pass completely though one 45° elbow, when it approached the second the guide wheel hub rotated too far from parallel, jamming the robot and leaving it unable to move in either direction. Instability of the articulations is at fault here, and some further adjustments of the stiffening springs would most likely be the cure. The failure of the robot to climb vertically is due to slightly less traction in these new wheels – early models using the LEGO wheels were able to make this climb (although the LEGO wheels could not be used in the final project due to a propensity to slide off of their shaft) – and it is hoped that new wheel springs in the drive section will yield enough normal force to allow the machine to meet this criterion.

Elbows of 90° remain impassable to the current vehicle. Some experiments will have to be conducted here; most promising here is the possibility of changing the order of segments, or removing some of the guide wheels entirely, as it was seen that placing the screw drive first allowed passage through such elbows (raising the difficulty of housing the video camera, of course).

The functionality of the electronics, including the inertial navigation units and the microcontroller with serial communication to a host PC, is best described as partial, as elements of both were functioning properly prior to the end of the project. Progress on inertial navigation did reach the stage where all three gyroscopes were being continuously sampled by the microcontroller, with the results being sent serially to a PC where dials representing each one's current position were represented on the screen. If one of the gyroscopes were to be rotated by half a turn, the corresponding dial for that one would, in response, rotate half a turn, etc. Also, testing of the final microcontroller program in RAM was successful when using the IDE program environment to communicate the control instructions, but the team did not have time enough to complete the application program for sending and receiving data to and from the robot. Unfortunately, certain last-minute difficulties relating to the wiring of the payload section precluded any demonstration of these successes at the final presentation given by the team.

Further testing of the prototype is necessary for the resolution of some of the minor design issues preventing the full attainment of the project's initial goals. For example, further adjustment of the spring joints between sections is needed to prevent the robot from jamming or buckling. Some of the power regulator boards will have to be repaired. Finally, it would be desirable to increase the number of electrical connectors between sections, allowing much more flexibility when wiring the complete robot.

V. Recommendations

Aside from repairing the on-board electronics and adjusting the vehicle so that it can meet all of its mobility goals, which the current team will undertake as a personal project in coming weeks, several enhancements might be considered by future investigators. For instance, ultrasonic, eddy current, or other sensors could be mounted on the robot for non-destructive testing of pipe integrity. Another useful feature would be two-axis control over the video camera, allowing the operator to examine the sides of the pipe closely; even better would be the inclusion of such a camera in the rear section as well, facilitating backwards travel and providing a view, possibly, of the robot itself so that mechanical difficulties or other issues can be diagnosed. Finally, it might be possible to enhance the mobility of the Pipe Crawler so that tee's and other fittings can be successfully negotiated – such improvements might consist of servo-motors that can direct the head and tail sections in order to initiate turns actively.

Perhaps students of energy and dedication can be found to continue this work and implement some of these ambitious ideas. Certain senior projects have acquired a sort of on-going status (the Baja car, web-controlled house, and following robot come to mind), some of them in active development over many years and across numerous versions. It is the hope of the members of team six that the pipe inspection robot might be among these worthy efforts in the future.

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