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# A system of launchable mesoscale robots for distributed sensing

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## ABSTRACT

A system of launchable miniature mobile robots with various sensors as payload is used for distributed sensing. The robots are projected to areas of interest either by a robot launcher or by a human operator using standard equipment. A wireless communication network is used to exchange information with the robots. Payloads such as a MEMS sensor for vibration detection, a microphone and an active video module are used mainly to detect humans. The video camera provides live images through a wireless video transmitter and a pan-tilt mechanism expands the effective field of view. There are strict restrictions on total volume and power consumption of the payloads due to the small size of the robot. Emerging technologies are used to address these restrictions. In this paper, we describe the use of microrobotic technologies to develop active vision modules for the mesoscale robot. A single chip CMOS video sensor is used along with a miniature lens that is approximately the size of a sugar cube. The device consumes 100 mW; about 5 times less than the power consumption of a comparable CCD camera. Miniature gearmotors 3 mm in diameter are used to drive the pan-tilt mechanism. A miniature video transmitter is used to transmit analog video signals from the camera.

**Keywords**: launchable, mobile, mesoscale, camera, pan-tilt

## 1. INTRODUCTION

The use of robots to remotely monitor hazardous environments is a primary application for autonomous robotic systems. A joint project between the University of Minnesota, MTS Systems Corp., and Honeywell Inc. is developing a new approach to this robotic task through the use of a novel distributed system of miniature mobile robots. These miniature robots are distributed throughout the environment through two separate methods of locomotion. A gross positioning method launches the robots through the air to an approximate location. After the robots land, fine motion capabilities that the robots posses allow them to move into appropriate reconnaissance positions. These miniature robots, called Launchable Reconnaissance Robots (LRR), contain various types of sensors as payloads and a wireless transmitter/receiver. In this paper we describe the active video module that was designed as a payload for an LRR. This is a challenging task due to the limitations required on size, weight, and power consumption. We discuss the various design issues and new technologies that enabled us to achieve our goal of providing live video information using active video sensors.

### 1.1. Launchable reconnaissance robots

LRRs are cylindrical in shape with an outer diameter of 40 mm and length of 80 to 100 mm. These dimensions allow the robot to be launched using standard equipment. There are two wheels at both ends of the cylinder that are driven by separate D.C. gear-motors. Another motor is used to retract a spring arm located outside the body. By quickly releasing the spring a hopping action of the robot is achieved. This locomotion method is intended to rescue the robot from obstacles that are too big to move over using the wheels. Figure 1 illustrates a prototype LRR.

The most important components of the LRRs are the various sensors that are carried as payloads within the shell. LRRs have

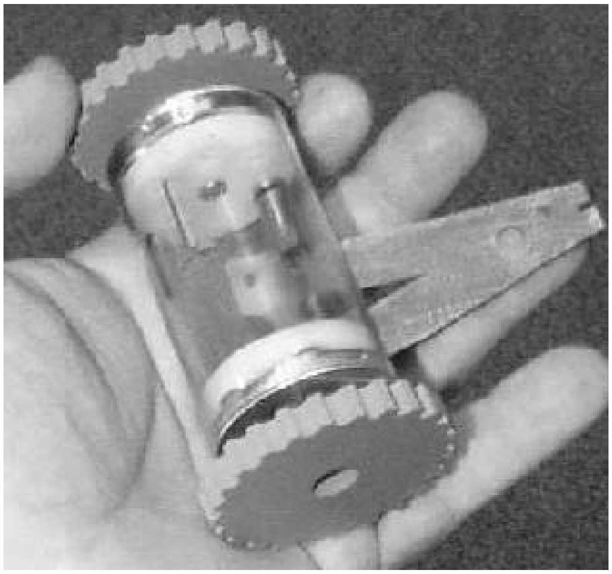

Figure 1. Launchable reconnaissance robot

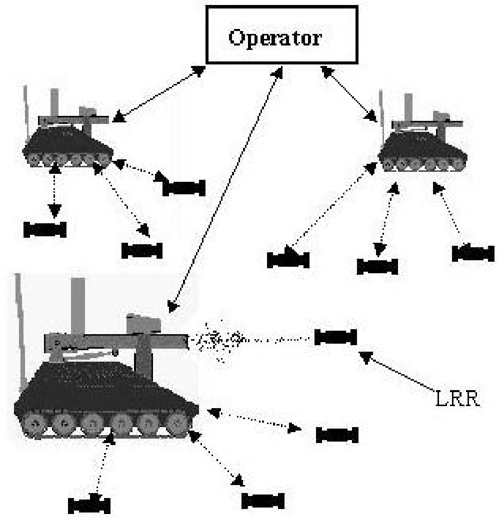


Figure 2. Distributed robotic system

a modular design so that different payload modules can be attached to the base robot for alternative functionality. These modules include vibration and toxic gas sensors using MEMS technology, microphones, and an active video module.

LRRs can be deployed either by individuals or by more sophisticated and larger mobile robots. They receive commands and transmit information through an RF data link. This allow the robots to form a distributed sensory network over the area of surveillance. Figure 2 illustrates this concept.

### 1.2. Active Video Module

The active video module consists of a miniature video camera, a wireless video transmitter and a pan-tilt mechanism. The camera is normally concealed inside the body to conserve the tubular form of the shell. It comes out of the body by opening a hatch and retracts when the robot is to be moved. However, the camera can still see through the transparent body of the robot.

The payload volume available for the video module is a semi-cylinder along the tubular body, having approximately 35 mm inside diameter and 18 mm length with a total volume of 8.7 $cm^3$. To fit inside such a small volume each component of the module must be miniaturized. Additionally, the maximum power available for payloads from the lithium batteries of the robot is 0.9 W (100mA @ 9V).

In the remainder of this paper we discuss individual elements of the active camera module surveying the available technologies.

## 2. VIDEO CAMERA AND TRANSMITTER

Video is a valuable information source for reconnaissance and surveillance purposes. Live or still images may be captured and sent back to a human operator. A video camera generates signals according to the light intensity on its sensor. Light rays from the scene are focused on the sensor plate by a lens system. Early video sensors were all tube-type devices and were expensive. An enormous reduction in cost, size and power consumption was achieved by the invention of the CCD sensor.

Another type of video sensor technology, the CMOS sensor, has emerged recently. Both CMOS and CCD sensors are solid-state devices made from silicon. They are based on the same principle of photoconversion to represent incident photons by charge. Unlike the CCD, the CMOS sensor detects the integrated charges in the pixels at the spot, without transferring them, using charge amplifiers made from CMOS transistors. CMOS is a well developed technology and all necessary circuitry for the camera can be integrated in a single chip at a reduced cost and power consumption [7].

An important feature of the sensor is on-chip automatic exposure control circuit. This circuit adjusts the integration time of the pixels (the duration while the photons hit the pixels and charges are collected before they are sampled and flushed) and eliminates the need for external mechanical shutter components. In other words, the camera electronically adjusts to ambient lighting conditions and no mechanical aperture in the lens system is needed. Since the video module will be used both indoors and outdoors this functionality is essential.

The power consumption of single chip monochrome CMOS video sensors on the market are typically between 100-200 mW. The power consumption of CCD sensors is typically 3 to 5 times this figure. The sensor we use is the OV5016 by OmniVision and consumes 20 mA at 5 V.

Color sensors are also available for both CCD and CMOS types. Color images do not contain considerably more information than grayscale images and in the case of the video module the increased power consumption makes this option unattractive.

A pinhole lens with 5.7 mm focal distance is used to focus the image on the video sensor. The resulting sensor-lens package is approximately 15x15x16 mm in size and weighs less than 5 gr.

CMOS vision sensors are also sensitive to near-infrared wavelengths. Using suitable LEDs for illumination, these sensors are useful for nighttime applications.

Table 1 summarizes the specifications of the video camera used in the video module.

**Table 1: Video camera specifications**

| | |
|---|---|
| Sensor type | Single-chip monochrome CMOS sensor with 320x240 pixels |
| Size | 15 x 15 x 16 mm |
| Power consumption | 20 mA at 6-9 VDC |
| Output | Composite video signal, 2 V p-p at 30 frame/s |
| Lens | Pinhole lens 5.7 mm focal length |

There are a number of wireless video transmitters available on the market, however, only those intended for covert video applications and hobby use are small enough to fit within the payload constraints. We use a miniature transmitter by Micro Video Products, Canada that transmits in the 900 MHz ISM (Industrial, Scientific and Medical) band and consumes 30 mA at 9V. The circuit board is about 24 x 17 x 8 mm in size. Its range was tested to be 150-200 ft line of sight indoors. However, the structure of the building will affect this figure.

## 3. ACTUATORS

Development of actuators for MEMS is an important research area. Several different actuators utilizing various physical phenomena have been developed. The effect of miniaturization on these actuators is dependent on the type of forces involved in actuation [15].

Common microactuators can be classified as actuators using electromagnetic and electrostatic forces and actuators using a functional element [10]. Examples of actuators with a functional element are piezoelectric and shape memory alloy (SMA) actuators.

Many of these microactuators may be applied to mesoscale systems millimeter to centimeter size. However, their effectiveness in this size may be different than it is in the micro domain. Additionally, some actuators may require high voltages or currents which limits their use in miniature mobile robots. Below, common types of actuators are analyzed from this perspective.

### 3.1. Electrostatic and electromagnetic actuators

Electrostatic force between two electrodes is proportional to the surface area of electrodes and inversely proportional to the square of the distance between them. Since these two scale equally but opposite to each other electrostatic forces are not effected from miniaturization. When electrostatic forces are compared to gravitational forces, as in the case of micro systems, they are considered suitable for actuation. However, high voltages (over 100 V) are typically needed to drive electrostatic actuators [10]. For a mesoscale system electrostatic forces are usually too weak to generate mechanical action.

Unlike electrostatic forces, electromagnetic forces, commonly utilized in all types of electric motors are effected from scaling by the square of the linear dimension. However, electromagnetic actuators may still be a good choice for mesoscale systems if the magnetic field density is high. Motors with rare-earth permanent magnets are typically used in such drives. As an example, a brushless D.C. motor by RMB has dimensions of 3 mm diameter and is approximately 10 mm length. Torques of $25.10^{-6}$N-m at 20000 rpm are achievable with this motor [5].

A gearbox at the output of the electromagnetic actuator is often necessary to increase the torque while reducing the speed. Typical reduction rates for commercially available gearmotors with a diameter below 5 mm are from 1:3.6 to 1:125 [6] [12]. A planetary micro gear system is often employed for increased reduction in a small volume. The elements of the gear box are too small to be machined by traditional methods. Wire Electro Discharge Machining (W-EDM) technology allows tooth modulus down to 20 microns using any conductive material. Gears made of Nickel manufactured by the LIGA process are also used in commercial motors [12]. The rotating shafts are usually made of steel and use jewel bearings.

### 3.2. Piezoelectric actuators

Piezoelectric elements generate strain due to an applied voltage across them. Nanometer resolution and large forces can be generated at frequencies of several kHz. However, the strain generated is around 0.1% and mechanical amplification of displacement is generally required. A mechanism working close to a kinematic singularity may be used to create large displacements from the small strain of the piezo element [4].

Another problem is the requirement of high voltages, typically around 150 V. Although power consumption may be low, special power electronics is required to generate these high voltages from typical battery supply voltages of mobile robots.

One distinct type of actuator using piezoelectric elements is the ultrasonic motor [13]. These types of motors have a rotor that rests on a stator made of piezoelectric elements. The stator is excited by a voltage signal to create travelling waves and cause a rubbing movement between the stator and the rotor. Typical characteristics of these motors are high torque at low speed and high holding torque due to friction between stator and rotor. They are also suitable for hazardous environments since no sparks are produced. The inherent high torque at low speeds eliminates the need for complex gear boxes in many cases.

### 3.3. Shape memory alloy actuators

Shape memory alloy (SMA) material is a metal alloy (commonly TiNi) with a shape-recovery characteristic. When the material is plastically deformed and then heated above a certain temperature, it recovers its original shape. This property is utilized to create various kinds of actuators. The SMA material is usually strained by a bias force and upon heating recovers its original shape by acting against the bias force. Stresses of 170 MPa and more can be generated this way. The bias force is adjusted to cause 4% maximum strain to minimize the decrease in the memory effect after many cycles. Tens of millions of cycles are possible at low strain [3].

The SMA provides simple and robust actuation within a small volume and weight. It is intrinsically an on/off type of actuator with two positions for high and low temperature states. However, research has been done to implement electric resistance feedback control in a SMA servo system [9].

One disadvantage of SMA is its relatively slow response especially during the cooling phase which is usually not forced. Bandwidths of approximately 4 Hz have been achieved by differential heating and using SMA wire both as actuator and as mechanical bias for restoration [8]. Another disadvantage for mobile systems with limited power supply is the typical current of several hundred milliamps required to heat the SMA material.

In the case of the active video module, the most restrictive requirements from the chosen actuation type are small volume, low current (100 mA peak), and low voltage (9 V max). The camera weighs less than 5 gr. and enough torque can be generated for the necessary pan and tilt action by any of the three actuation types mentioned above. An ultrasonic motor has good torque, speed, and holding torque specifications for this purpose, however the need for power electronics to increase the voltage and driver circuitry to generate appropriate signals does not comply with the small volume available.

A mechanism driven by a shape memory alloy actuator would have the advantage of simple and thus reliable operation. However, the camera is to be tilted and panned within a range, and intermediate positions must be held without consuming power. SMA actuation can still be useful for simple mechanisms like bistable latches for locking and releasing spring actuated hinges.

An electromagnetic actuator was chosen to drive the pan-tilt mechanism of the active video module. It is a brushless D.C. gearmotor by RMB. The motor has a diameter of 3.4 mm and length of approximately 15 mm. A 3 stage planetary gearbox provides 1:125 reduction and a continuous output torque of 2.2 mNm [6]. The total gearhead efficiency is 60%. Since the motor is brushless, commutation is done externally by a microprocessor based drive circuit, also supplied by the company. However, the on board processor of the robot is likely to take over this job. Peak power consumption is 70 mA at 5 V.

## 4. PAN-TILT MECHANISM

The usual design of a pan-tilt mechanism has two actuators for each axis of motion. Usually the pan motor carries the tilt motor and the camera. These types of pan-tilt actuators are frequently used for security monitoring. They are also used by computer vision and robotics researchers for active vision. These systems are generally big, heavy and slow. Additionally they do not incorporate any position feedback sensor. Some alternative designs were made [1], for example a linear stepper motor controlled platform pan-tilt actuator and a spherical pointing motor (SPM) The latter consists of a miniature camera with a permanent magnet mounted on a gimbal. Three sets of coils are wounded outside the gimbal in orthogonal directions. By controlling the individual currents to each coil a magnetic field vector of desired orientation is produced. The permanent magnet on the gimbal (and thus the camera) aligns itself with this vector. The camera can be rotated by step sizes of $0.011^{o}$. However, the SPM weighs 160 gr. and requires about 1A current.

The active video module transmits live images back to a human operator and the pan-tilt action is also controlled by this operator. Therefore highly accurate motion or position feedback is not essential. On the other hand, the camera should normally be concealed inside the robot body, come out when needed, and retract before the robot moves.

The general design of the pan-tilt mechanism is shown in Figure 4. Three miniature motors are used independently to generate the pan, tilt and camera pop-up/retract motions. The tilt motor is directly coupled to the camera and the pan motor rotates both. A parallel four-bar mechanism is actuated by the third motor to extend and retract the camera. The four-bar is driven by a lead-screw which has inherent self-locking capability. The operation of the mechanism is illustrated in Figure 5. A small portion of the transparent shell, not shown in the figure, covers the camera while it is retracted and moves together with it. Small contact switches, not shown in figure, limit the travel of the actuators.An early prototype of the pan-tilt mechanism is shown in Figure 3.

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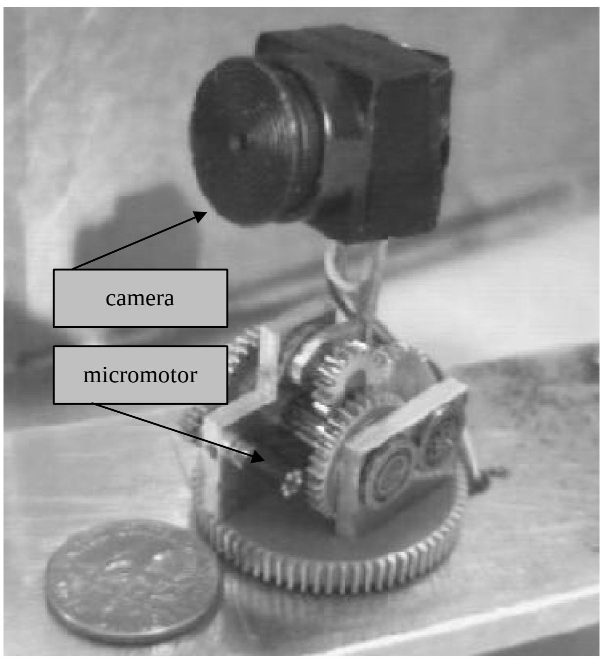


**Figure 3. Camera and Motor**

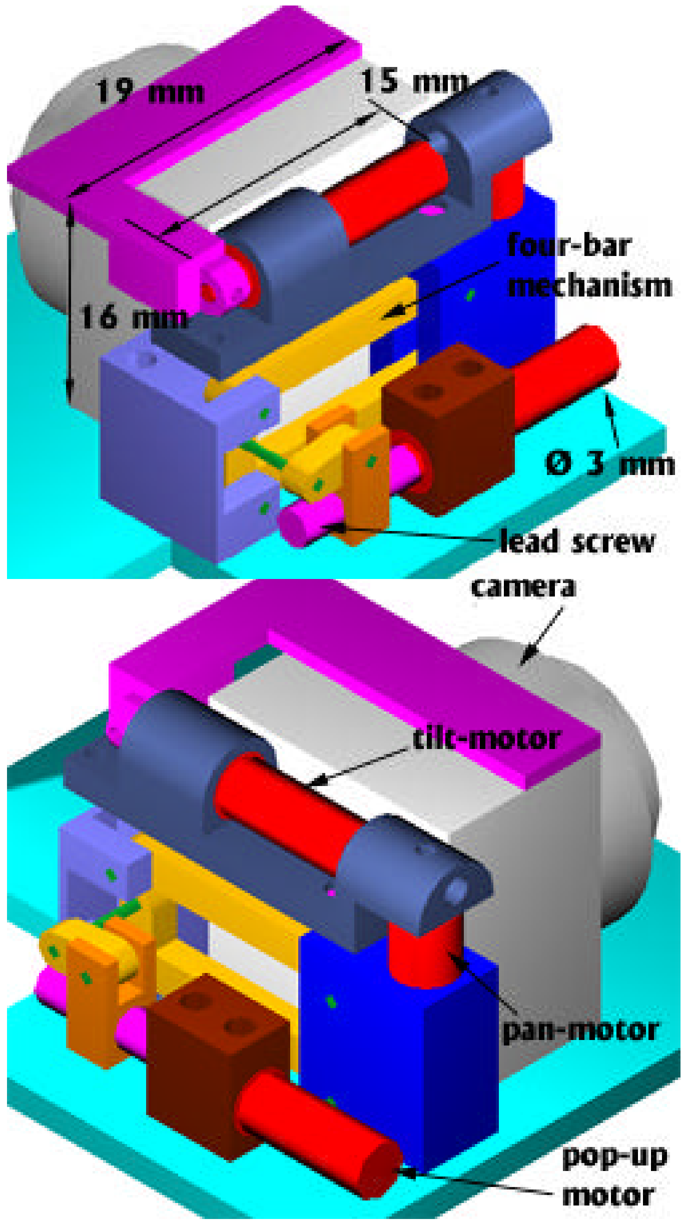


**Figure 4. Pan-tilt mechanism**

## 5. APPLICATIONS AND FUTURE WORK

The primary application of the launchable reconnaissance robot is surveillance and especially detection of humans. Currently the images acquired from the robots are inspected by human operators but the goal is to bring more autonomous behavior using advances in technology and computer vision.

Image processing is by its nature a computationally expensive task. However, using digital video cameras and powerful microprocessors it is possible to have embedded vision systems suitable for miniature mobile robotic applications. One example is the Eyebot from the University of Western Australia [2]. This platform employs a digital camera with 80x60 pixels and a Motorola 68332 32-bit microcontroller for control of mobile robots and processing of visual data.

Digital transmission with image compression is another advantage of using digital cameras. A micro camera system compromising a CMOS grayscale sensor with 312 x 287 pixels, A/D converter, processing interface and pipelined processing architecture was built into a package size of 20.6 x 15.75 x14.7 mm [11]. The total processing power of the camera is 70 MIPS (million instructions per second). It can be programmed to perform real-time image enhancement, image encoding or motion triggered acquisition.

Active camera systems have been used for motion tracking. Motion based tracking systems have the advantage of being able

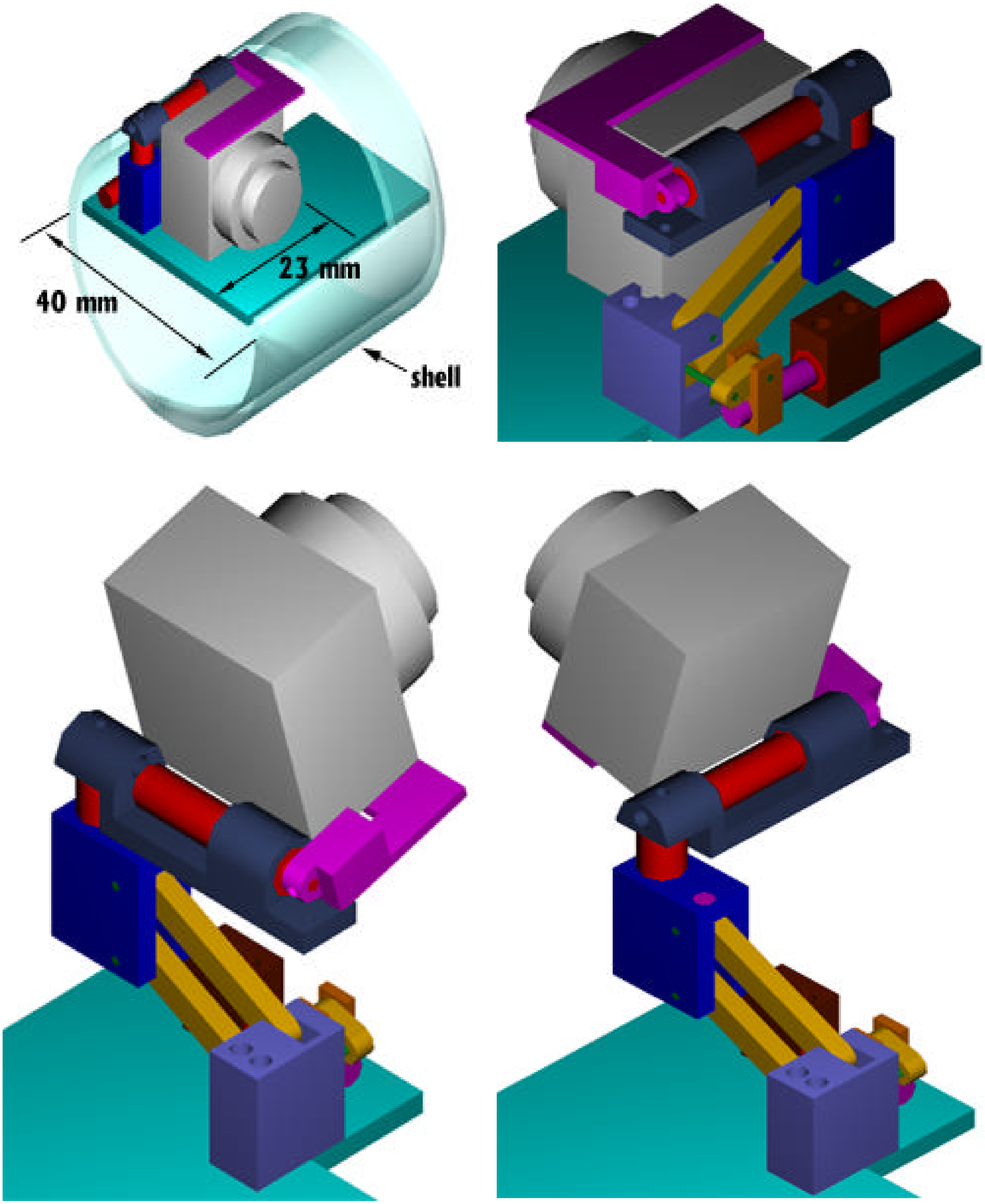


**Figure 5. Mechanism operation**

to track any moving object regardless of shape and size [14]. Unlike recognition based systems they can be used effectively in uncontrolled environments.

Our future goals include digital image acquisition, on-board image processing and implementing active vision techniques with the vision module.

## 6. CONCLUSION

A miniature active video module for a launchable mobile robot was designed. Different types of video sensors were inspected and various forms of micro actuation were analyzed for their compatibility in a mesoscale robotic system. Applications and future improvements of the video module were discussed.

## 7. ACKNOWLEDGMENT

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