# Leveraging the Nanogram League RoboCup Competition in the Undergraduate Classroom

**Jenelle Armstrong Piepmeier** **Samara Firebaugh**
Weapons and Systems Engineering Electrical Engineering
United States Naval Academy
Annapolis, MD 21402

**Abstract**

The newly organized RoboCup Nanogram competition challenges teams of students and researchers to construct microscopic untethered robots that will compete against each other in soccer-related agility drills on a 2.5mm×2.5mm playing field. With dimensions in the measured in tens or hundreds of micrometers and masses measured in nanograms, these microrobots will be controlled with visual feedback from an optical microscope. This competition poses many interdisciplinary educational opportunities in the areas of microelectricalmechanical (MEMS) devices as well as the area of vision-based robotic control. This paper focuses on some of the educational opportunities presented by this competition. These opportunities span the disciplines of electrical and system engineering including microfabrication, feedback control system design, and computer vision.

## Introduction

As delineated in the competition website [1], the demonstration competition to be held at the Georgia Institute of Technology in July 2007 will consist of three compulsory events:

1. The 2 Millimeter Dash
2. The Slalom Drill
3. The Ball-Handling Drill

In addition, teams can demonstrate coordinated motion of multiple devices in the RoboCup Dance event. Opponents or defenders consist of a thick film of photoresist that is patterned at varous points on the field of play, and thin-film discs of silicon nitride serve as balls.

Each player must fit within a bounding box measuring 300 micrometers on a side and must be capable of operation on the playing field without the presence of any physically connected wires or tethers.

## Microrobots

The microrobot used for the competition, illustrated in Figure 1, is similar to that developed by Donald *et al.* at Dartmouth [2]. The microrobots are 60 μm by 250 μm by 10 μm, and they are controlled through coupled electromagnetic fields generated by an interdigitated electrode array on the "playing field." Forward motion is accomplished via a "scratch drive actuator." Such actuators consist of a plate with a bushing at the front end. When a potential difference is applied between the plate and the substrate, the plate bows down to the substrate. When the potential difference is released, the plate springs back, and in the process moves forward a step. The motion is similar to an inchworm. Thus an alternating voltage signal is used to repeatedly step the robot forward. Turning is accomplished by bringing the stylus arm down in contact with the substrate while stepping the robot forward, so that the robot moves in an arc with the stylus at the center of curvature.

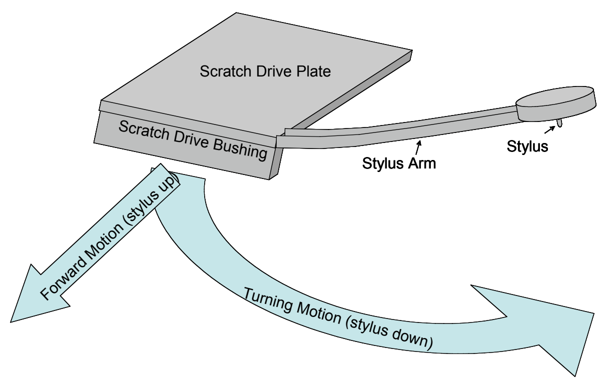


**Figure 1 Illustration of Microrobot**

The microrobots are built using a surface micromachining process. In surface micromachining, structural layers of polysilicon are alternated with sacrificial layers of silicon dioxide. After each layer is deposited, it is patterned using chromium masks. Polysilicon layers can be connected through holes patterned in the oxide layers. In the last step of the process, the oxide is removed using hydrofluoric acid, releasing the structures. This process is illustrated in Figure 2.

A commercial fabrication process, for which the students designed the masks, was used for most of the device manufacture. In order to design the mask set, the students had to fully understand the commercial process sequence and develop and use design equations for the scratch drive and stylus arm. An additional chromium layer not available in the commercial process is required in order to achieve the independently controlled turning arm. This final layer will be deposited and patterned in the campus microfabrication laboratory. The students will also perform the release step. This combination of commercial and student processing allows for the students to have some hands-on exposure to microfabrication while at the same time allowing them to form a more complex device than would otherwise be possible within the short time span of a semester.

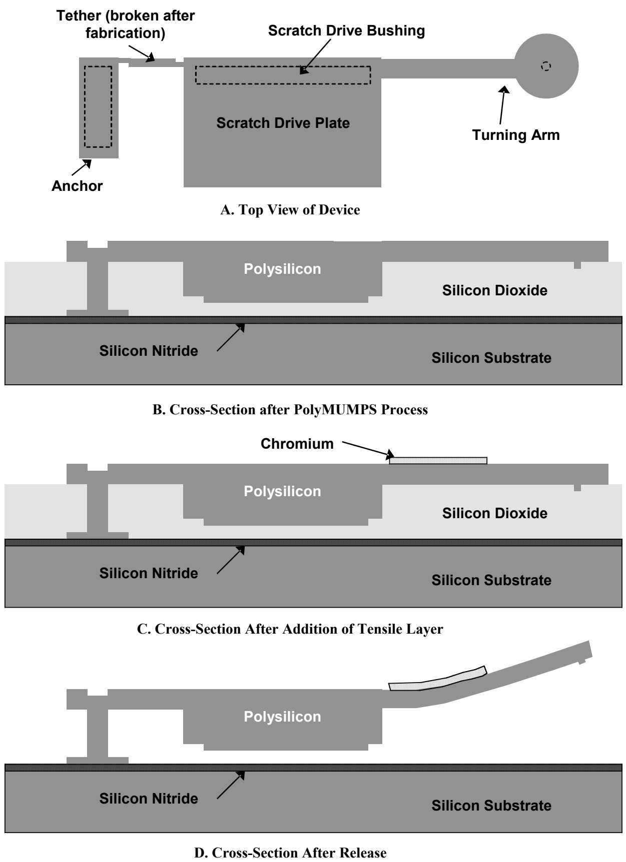


**Figure 2 Illustration of Microrobot Manufacture**

## Micro Mobile Robot Control

The microrobot described in the previous section can be modeled as nonholonomic mobile robot limited to forward motion and left turns. The state of the robot is $(x,y,\theta)$, where $(x,y)$ is the location of the robot and $\theta$ is the orientation of the device. The robot kinematics may be modeled similarly to differential drive robot with a forward velocity $v$, an angular velocity ω, a radius of curvature $R$ as discussed in [5].

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} \cos\theta \\ \sin\theta \\ 0 \end{pmatrix} v + \begin{pmatrix} 0 \\ 0 \\ \frac{1}{R} \end{pmatrix} \omega$$

where both $v$ and ω are bounded and positive. As discussed in [4], the radius of curvature can be varied by alternating the relative percentage of the two voltage waveforms that moves the robot either forward or in a turn within a short time period.

Given an ideal device with constant forward and angular velocities, the time optimal trajectory between any two points with arbitrary orientations could be accomplished as a {left turn, forward, left turn} sequence. However, each device varies in forward and angular velocity during operation; variations may be as much as ten percent depending on the device and the stepping frequency of the drive waveform.

Students need to develop both a path planning and feedback control scheme to control the microrobots to score goals and avoid obstacles while handicapped to forward motion and left turns.

## Computer Vision

Planning and controlling the microrobot motion requires visual feedback from the camera mounted on a microscope viewing the field of play. The computer vision task consists of locating the position and orientation of the microrobot, the location of the ball, and the presence and location of any obstacles. These are tasks well within the scope of undergraduate students. As shown in Figure 2, thresholding or optical flow can be used to isolate the microrobot, morphology can be used to clean up the image, and simple features such as centroids, area, and orientation can be found to identify the necessary data for trajectory planning and control. Using a captured video sequence of the robot, students prototype image processing algorithms using MATLAB®, Simulink®, and the Video and Image Processing Blockset. Figure 2 shows a sample microrobot with the detected centroid, bounding box, and a heading or orientation line superimposed on the image.

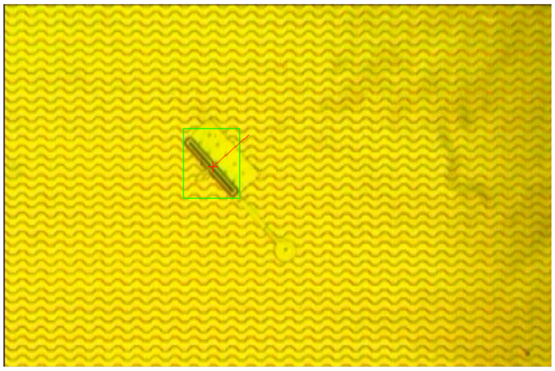

**Figure 2 Microrobot with detected centroid, bounding box, and orientation.**

This project also provides a number of opportunities for application-related system integration discussions. For instance, camera selection is a very practical skill not discussed in textbooks. Students in a computer vision class discussed the necessary resolution and video signal format. Commercially available cameras for machine vision usually have CMOS or charge coupled device (CCD) sensors, and the choice depends on the nature of the application. In this case, the superior image quality of a CCD makes it the better choice. Minimum resolution can be determined using the following formula.

$$resolution_{\min} = 2\frac{FOV}{smallest\ \ feature}$$

where the field of view (FOV) and the smallest feature of the microrobot are described in the same units (pixels or meters). This formula insures that the smallest feature is at least two pixels wide. Larger multipliers may be used for a factor of safety.

## Summary

While student designs for the microrobot and the vision-based control system are still in their infancy, the challenges of the new Robocup Nanogram League are already providing an interesting context for undergraduate learning about feedback control, computer vision techniques, and microfabrication methods.


## Acknowledgements

The authors would like to thank Craig McGray of National Institute of Standards and Technology for video of working microrobots.


## References


[1] http://www.eeel.nist.gov/812/nanogram

[2] Donald, Levey, McGray, Rus, and Sinclair, “Power Delivery and Locomotion of Untethered Micro-Actuators”, *Journal of Microelectromechanical Systems*, vol. 12, No. 6, 2003, pp. 947-959

[3] Memscap, Inc., http://www.memscap.com

[4] Donald, Levey, McGray, Paprotny, and Rus, “An Untethered, Electrostatic, Globally Controllable MEMS Micro-Robot”, *Journal of Microelectromechanical Systems*, vol. 15, No. 1, 2006, pp. 1-15.

[5] Laumond, J.-P., Ed. 1998. *Robot Motion Planning and Control*. Springer-Verlag.