Workshop on Nanosensors: Self-Organization and Swarm Robotics
Third International Conference on Nano-Networks (Nano-Net 2008)
Radisson Hotel Boston (Boston, Massachusetts)
September 14, 2008

8:00 – 9:00: BREAKFAST AND REGISTRATION

9:00 – 10:30: Session 1: Overview

Title: Harnessing the Swarm – From Ants to Robots (Welcome)
Speaker: Sanjay Goel
Affiliation: University at Albany, SUNY (UAlbany)
Abstract: The dream of having smart dust is finally within reach with the arrival of nano-technology. To realize these drams, however, we need to address several fundamental issues. Despite miniaturization of sensors, the limitations on power and communication remain. Expecting an independent power source and long range communication for each sensor is neither feasible, nor possible with current technology. Self-organization, however, holds promise in making networking of sensors feasible. Self-organization has been studied in several domains such as, social insects, physics, and … We need to draw from all of these fields. Theories of self-organization have been attempted using Kolmogorov Complexity, statistical mechanics, and cellular automata for specific domains; however, we still lack a universal theory of self-organization. The goal of this workshop is to bring together researchers from different domains and build an understanding of the role of self-organization in sensors. We want to start a dialogue and perhaps begin to collaborate to make advances in nano-sensor communication and self-organization. Our long term goal is to develop a universal theory of self-organization. We have worked on developing optimization algorithms using cellular automata. I am currently working on problems in nano-sensors as well as transportation using self-organization algorithms.

Title: Self-Organization and Nanoscale Networking
Speaker: Stephen F. Bush
Affiliation: GE Global Research
Abstract: I suggest specific goals and objectives that this workshop may wish to achieve regarding nano-communications and self-organization. Namely:

(1) What are the merits and demerits of existing hardware platforms and common testbeds for automated swarm inspection?
(2) What standards that are needed to move small-scale swarm inspection into mainstream use?
(3) What is the fundamental relation between communications in swarm behavior?
(4) Why have swarm-like and other "emergent" simulation software (e.g., Swarm and RePast) failed to provide significant insight into emergent behavior of such systems after so many years of development?

In particular, I would like to open discussion on how self-organization and nano-communcations are inter-related: (1) should self-organisation and nano-communication be considered orthoganal processes and (2) what are some common characteristics of nano-communcation channels?

Title: Nano Robotics: From Science Fiction to Reality (Keynote)
Speaker: Constantinos Mavroidis
Affiliation: Department of Mechanical and Industrial Engineering, Northeastern University, Boston MA
Abstract: This talk will present the state of the art and future challenges in the field of nano-robotics. Nano-robots are controllable machines at the nano (10^{-9}) meter or molecular scale that are composed of nano-scale components. With the modern scientific capabilities, it has become possible to attempt the creation of nanorobotic devices and interface them with the macro world for control. There are countless such machines that exist in nature and there is an opportunity to build more of them by mimicking nature. A roadmap towards the progression of this field from science fiction to reality is described and some design concepts and philosophies are illustrated. There are many applications for nanorobotic systems and its biggest impact would be in the area of medicine.

Furthermore, we will present the design hypothesis, architectures and computational results of a novel protein based nanoGripper that could eventually serve as a component of a bionanorobotic system. Our goal was to engineer nanoGrippers that are inspired by nature and could be used in various biological, chemical and nano-manufacturing applications. We first characterized a natural peptide motif that could act as a template for designing nanoscale grippers due to its structure, stability and specificity at various physio-chemical conditions. We then altered and improved the functionality of these natural elements using protein engineering, which leads to protein-based nanoGrippers with optimal performance characteristics.

10:30 – 11:00 BREAK

11:00 – 12:15: Session 2: Swarm Robotics I

Title: Swarm Robotics for Construction Tasks
Speaker: Aristides A. G. Requicha
Affiliation: Laboratory for Molecular Robotics, University of Southern California, Los Angeles, CA
Abstract: This paper presents algorithms and simulations for construction tasks executed by swarms of self-assembling robots. Our robot models are minimalistic, and attempt to capture the properties that nanorobots of the future are expected to have. The robots have small memories and very simple programs, and are capable of communicating with one another only when they are in contact. All robots are identical, and all have the same program. This program is automatically computed by a compiler whose input is a desired, or goal geometric shape in the plane, and whose output is a set of rules that direct the robots.

We have experimented with two types of robot models and algorithms. The first type uses Finite State Machines (FSMs) as robot programs. We succeeded in building interesting structures with FSM robots, but were not able to make the shapes self-repairing in the presence of gross disturbances. The second model uses purely reactive robots, with no state, and relies heavily on inter-robot communication. We have shown that this approach has some remarkable properties: any robot that starts messaging can serve as a seed for the structure; robot failure or external interference with the construction process are tolerated, and the structure heals itself; breaking a structure into pieces leads to regeneration and "reproduction", similar to cell mitosis.

We envisage applications such as the construction of scaffolds for building electronic circuitry at the nanoscale, or, on a more futuristic vein, for building or repairing biological structures such as bones or other organs. In the talk we will present algorithms, examples, and videos of simulations that validate the algorithms. (Joint work with Daniel J. Arbuckle.)

Title: Towards Inspection of Industrial Machinery with Miniature Robotic Swarms
Speaker: Nikolaus Correll
Affiliation: Distributed Robotics Laboratory, Massachusetts Institute of Technology, Boston, MA
Abstract: Autonomous inspection of machinery receives considerable interest from industry due to the potential reduction of downtime and by the prospect of moving from a schedule-based to a condition-based maintenance cycle that allows for distributing down-time into periods with low usage on the machine. Inspection usually requires complete sensor coverage of the areas of interest, which is a canonical problem in robotics research. In this talk, I will present a series of algorithms for multi-robot boundary coverage. The boundary coverage problem is motivated by the autonomous inspection of jet turbines by a swarm of miniature robots. Algorithms range from reactive, non-collaborative to deliberative collaborative algorithms with close-to-optimal performance, and have been validated on a fleet of miniature robots each smaller than one cubic-inch. Emphasis of this talk will be on trade-offs concerning performance and reliability vs.
computational, locomotion, and communication requirements on the individual robot.

12:15 – 1:30 LUNCH (ROUND TABLE)

1:30 – 2:45: Session 3: Swarm Robotics II

Topic: Miniature Mobile Robots Down to Micron Scale
Authors: Metin Sitti
Affiliation: Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA
Abstract: Miniature mobile robots have the unique capability of accessing to small spaces and scales directly. Due to their small size and small scale physics and dynamics, they could be agile and portable, and could be inexpensive and in large numbers if they are mass produced. Different scale miniature robots with various locomotion capabilities are presented in this talk. Network or swarm of these miniature robots would have applications in the fields of mobile sensor networks, environmental monitoring, health-care, inspection and maintenance, space, security, entertainment, and education. First, as palm-size and centimeter scale robots, miniature climbing robots using gecko foot-hairs inspired micro/nano-fiber adhesives as their repeatable and power efficient attachment materials are proposed. Polymer elastomer micro-fiber arrays with angled and mushroom shaped tip endings and nanoscale and molecular scale polymer fibers on top of the micro-fiber tip endings are demonstrated. These

synthetic adhesives are as strong as biological gecko foot-hairs on smooth surfaces. Various climbing robot designs using these adhesives show the feasibility of fibrillar adhesives based climbing on smooth and micro/nanoscale rough surfaces in air or vacuum. Next, going down to tens or hundreds of micron scale robots, significant challenges are on-board actuation principles and power sources. As two alternative approaches, first, external powering and actuation are used to move permanent magnet 100 micron scale robot bodies on planar surfaces in air or in liquid in 2-D. As the next approach, a hybrid (biotic/abiotic) actuation principle is used to propel micron scale robotic bodies in liquid by harvesting the flagellar propulsion of attached bacteria and the chemical energy in the environment. Randomly attached bacteria are shown to propel 10 micron diameter polystyrene beads at an average speed of 15 μm/sec stochastically. Stop-and-go propulsion control of bacteria attached beads is demonstrated using chemical stimulus where heavy metal cupper ions hinder their propulsion while ethylenediaminetetraacetic acid resumes their motion. To improve the speed and direction performance of the bacteria attached micro-robotic bodies, micro/nano-patterning methods are proposed.

Paper: Role of Wireless Communications in Networking and Motion Control of Micro Robot Swarm
Authors: Shinsuke Hara, Tatsuya Ishimoto, Masaya Kitano and Tetsuo Tsujioka
Affiliation: Graduate School of Engineering, Osaka City University, Osaka Japan
Abstract: The role of wireless communications in robot swarm is not only to network all member robots for sharing sensed information on the outside world but also to send control information for their motions. Here, information networking and controlling are complementing each other. That is, the purpose of networking by wireless is to control the motions of all member robots correctly whereas that of motion control is to maintain reliable communications among them in erroneous wireless channels. This paper discusses the roles of wireless communications in micro robot swarm and introduces some results obtained through computer simulations and experiments with a prototype robot swarm.

2:45 – 3:15 BREAK

3:15 – 5:15 Session 4: Sensor Self-Organization

Paper: Self-Organizing smart dust sensors for planetary exploration
Authors: John R Barker and Fernando Rodriguez-Salazar
Affiliation: Nanoelectronics Research Centre, Dept. of Electronics and Electrical Engineering, University of Glasgow, Glasgow, Scotland, United Kingdom
Abstract: Smart Dust has been conceived as a system of millimeter scale autonomous devices that form the basis for massively distributed wireless sensor networks [1] and [2]. In the present paper we review our proposed development of Smart Dust as self-organised swarms of miniature communication/sensor devices useful for remote monitoring in space exploration [3]. The underpinning miniaturised wireless/ computing network technology required is very similar to nanotechnology systems, known as Smart Specks (part of a large consortium in Scotland [4]) that are already being fabricated at the University of Glasgow Nanoelectronics Research Centre for applications in collective computer intelligence, wireless distributed systems and smart RF-ID tagging. In our *space* application we address the key requirement of how smart dust motes can be enabled to move in synchronisation and to navigate over large distances autonomously. We first observe that with diameters and densities comparable to sand particles the behaviour of *passive dust* is comparable to the movement of airborne sand which has a considerable range on earth and on planets such as Mars [5, 6]. A possible application for *smart dust* would be to launch several tens of thousands of smart dust elements into a wind borne environment on a remote sensing mission involve navigation and data gathering/sensing over a period of time. Casualties would be inevitable. Finally, the surviving smart dust swarm would re-group into a phased array for transmission of data back to a remote spacecraft. The wireless networking of such a system is critical and complicated by the short range of available transmitter technologies and appropriate power supplies. Harvesting of local power has been investigated for: solar power, microwave absorption and collisional self-charging. However, the central problem is how to arrange for the collective self-organised motion of the smart dust ensemble in the presence of hostile terrain and weather. We have investigated the possibility of dynamically changing the shape of the smart dust elements so as to permit controlled navigation. Algorithms have been devised for the *adaptive shape change* of smart dust modes that permits a change in drag coefficient depending on location and heading. Monte Carlo simulations were performed for passive and smart dust [3] for swarms of smart dust devices transporting in the wind-dominated environment of the Martian landscape. It is concluded that relatively simple shape changing algorithms with nearest neighbour wireless communications augmented by longer range *Small Worlds* links are sufficient for long-range synchronised navigation. Practically all

the energy requirements are met by entrainment of the smart dust in the wind flow provided reasonable fluctuations exist. The implementation of the shape-changing has been investigated experimentally and theoretically through the use of an electro-active polymer sheath encasing each mote. As a bonus this methodology also is a basis for energy storage through impacts with passive sand. We are also studying scaled-down versions of self-organising smart dust for applications in liquid environments. A scaled-up version for application to probes to distant solar systems is also under study.

[1] B.A. Warneke, K.S.J. Pister, Proc. IMEC2002 ASME Int. Mech. Eng. Congress & Exposition, New Orleans, Louisiana, November 17-22, 1-4 (2002)

[2] B.A. Warneke, K.S.J. Pister, Solid States Circuits Conf. 2004 (ISSCC 2004), San Francisco, Feb. 16-18, 2004, session 17.4. (2004)

[3] J.R. Barker and A. Barmpoutis, J. Computational Electronics,3, 317-321, (2004)

[4] SpeckNet - Publications: http://www.specknet.org/publications/

[5] R.A. Bagnold, The physics of wind blown sand and desert dunes, Chapman and Hall, (1954).

[6] R. Greeley et al, Mars, ed H Kieffer et al, Univ. of Arizona Press, Tucson, 730-766 (1992).

Topic: Protoswarm: a Programming Language for Programming Swarm Robotics

Authors: Jonathan Bachrach

Affiliation: Makani Power

Abstract: Swarm robotic systems are becoming increasingly prevalent, but programmability is a major barrier to their deployment. Present systems force programmers to think in terms of individual agents. Application code becomes entangled with details of coordination and robustness and often does not compose well or translate to other domains. We offer an alternate approach whereby the programmer controls a single virtual \emph{spatial computer} which fills the environment space. The computations on this spatial computer are actually performed by a large number of locally-interacting individual agents. This abstracts the actual computational hardware behind the spatial computer interface, and allows the programmer to focus on a single model of global computation. We achieve this abstraction with two components: a language that embodies continuous space and time semantics and a runtime library that implements these semantics approximately. We demonstrate the efficacy of our approach with multi-agent algorithms in both simulation and on a group of 40 robots.

Topic: Optically Active Nanomaterials for use as Chemical Sensors

Author: Michael Carpenter

Affiliation: University at Albany, SUNY (UAlbany)

Abstract: Optically active nanomaterials can be tailored for a variety of sensing applications that are of interest for the development smart self organizing sensor networks. Our particular efforts in this area are related to two specific chemical sensing programs: 1)The development of hydrocarbon sensors for groundwater, soil and air monitoring and 2) Nanocomposite materials for the detection of gases in harsh environments. These two sensing studies will be discussed in light of the future development of self organizing sensor networks and in particular to the needs of swarming characteristics.

1) The impact of hydrocarbon pollution on human health and environmental health at ppt to ppm levels, highlights the need for fast, sensitive and selective hydrocarbon detection systems for environmental impact studies as well as the early detection of diseases. The hydrocarbon sensing properties of tailored CdSe semiconductor quantum dots (QDs) are currently being studied to determine their dependence on specific surface enhancement groups. Specifically detailed studies will be presented which detail the sensing properties of surface tailored QDs as a function of aromatic surface groups. Detailed PL studies have been completed which provide clear demonstrations of detection limits, sensitivity and selectivity for xylenes, toluene and benzene between 15 and 9400 ppm as a function of the phenyl group to QD surface distance.

2) The development of novel harsh environment compatible chemical sensing technologies is of critical need for optimal control of future zero emission power plants and low emission jet turbine engines as current sensor technologies cannot withstand these environments. As an alternative sensing technology gold nanoparticle embedded yttria stabilized zirconia (Au-YSZ) nanocomposite films have been deposited on optically transparent sapphire substrates. The Au nanoparticle surface plasmon resonance (SPR) band was monitored as concentrations of O_2, H_2, NO_2 in N_2, were varied and flowed over Au-YSZ films at elevated temperatures (~500 °C). Detectable changes in the SPR band were observed for all of the test gases as long as the temperature was greater than ~350 °C. Extensive O_2/H_2 and O_2/NO_2 titration experiments were performed and will be discussed in terms of

reactions occurring between exposure gases, Au nanoparticles and YSZ, which result in charge transfer to and from the Au nanoparticles upon concentration changes in gas exposure environment.

6:00 – 7:30 DINNER