An Autonomous Multi-Agent Testbed using Infrared Wireless Communication and Localization

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***Abstract*— The Autonomous Robotics and Control Systems Laboratory at the University of Washington has developed a testbed consisting of seven K-Team Khepera II miniature robots, a global vision system and a custom-designed infrared communication structure. The purpose of the testbed is to provide a platform for the real-world testing of distributed and centralized control algorithms for groups of autonomous robots. The testbed enables experiment design and execution to take place in an efficient and rapid manner. This paper describes the testbed components, most of which are available commercially. The new infrared communication turret is described in detail.**

***Index Terms*—Test bed, multi-agent robots, autonomous robots, infrared communication, localization**

I. Introduction

Autonomous robots working together allow for addressing increasingly complex tasks at a higher robustness over single robot systems. Redundancy in agent function also adds a degree of robustness to tasks in which the probability of loss of an agent is high. The Autonomous Robotics and Control Systems (ARCS) Laboratory at the University of Washington has created a multi-agent testbed with the intent of researching centralized and distributed control algorithms as well as robotic evolution of language and understanding of the environment.

The original motivation behind the creation of a hardware testbed is an ongoing research effort investigating communication activity in a distributed set of agents [1]. The efficiency of communication between agents is seen as a limiting factor in scalability in terms of power consumption and in terms of convergence to a solution to the task being performed by the distributed population of agents. Communication has been shown to improve the performance of multi-agent systems; however it also increases system complexity [2]. A variety of issues associated with communication in multi-agent systems are current areas of research. These issues include:

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- Imperfect Communication [3]
- Local Sensing [4][5][6]
- Clustering [6][7]
- Symbol Grounding and Anchoring [8]
- Consensus Tasks [9]
- Communication Learning and Evolution [10]
- Surrounding Unknown Objects [11]
- Box Pushing [12]
- Modeling of communication phenomena found in nature

The motivating factor for creating the hardware testbed was the ability to investigate all of these issues in a real-world, hardware setting. Much work in multi-agent systems today takes place only in simulation. If it is ported to hardware simulations, it typically only involves two or three agents at most.

Custom software created in the ARCS lab has been used to carry out simulations investigating the relationship between agent communication activity and agent cluster size. These agents exist in a predatory-prey environment where the movements are evolved using a Mamdani-type fuzzy inference system. Clustering is driven by probabilistic predation and starvation forces and subsequently compared

Fig 1. The Khepera II miniature robot (70mm diameter).

with communication activity. A high degree of correlation between these two factors has been observed in the software simulations [1].

The hardware testbed is being designed in part to compare these computer simulation results to that of a real, physical interaction. This testbed consists of several small robots, a wooden table with walls around the perimeter, a camera located centrally above the table linked to a computer for video processing, and a robot-to-robot as well as robot-to-computer infrared communications link.

Seven K-Team Khepera II miniature robots [5] were purchased so that the focus of the research could be placed upon writing and testing control algorithms rather than building a custom, in-house platform (Fig 1). These robots were chosen for their very small footprint, powerful features, high-quality design and room for expansion. Khepera robots have been used by dozens of other researchers around the globe researching such topics as cognition, education, multi-robot coordination, computer vision, intelligent control system algorithms (listed found in [14]).

The playing surface is a simple seven-foot square area framed around the perimeter by four-inch tall walls. This large area permits the research to expand to larger groups of agents in the future. Also, the table can be broken up into smaller segments for parallel simulations or to be transported for the purposes of off-site educational demonstrations.

To simulate robot-to-robot communication, line of sight infrared communication was chosen. The advantage of infrared over a stronger, more robust scheme such as RF transceivers is a physical operation similar to sound. The signal is directional and easily attenuated. Also communication range can be limited and subjected to objects and reflections. Differentials in infrared reception of communication along with the strength of the signal lend to a method of identifying the source of the transmissions. Conversely, radio frequency communication is generally omnidirectional and would be considered uniform in strength across the table in which the agents cohabitate.

A vision system is included in the testbed to provide the robots with position and angle information. A dedicated computer receives and processes video frames using proven color classification software provided by Carnage Melon University [6]. In general, this software classifies colors and creates regions upon which centroids are extracted. An algorithm groups the regions in such a way that robot positions and, with further processing, angles can be calculated. The resulting data is streamed to all robots on the table via an infrared transceiver connected to the master computer.

The main contribution provided by this research is the presentation of a custom-designed infrared communication turret that can be used on the Khepera II autonomous mobile robots for robot-to-robot communication and for robot localization. The initial design of a hardware testbed for the autonomous mobile robots is also presented.

The outline of the paper is as follows. In Section II, the Khepera robots are described. In Section III, the vision system that was created to provide the robots with simulated GPS data is described. In Section IV, the infrared system as a means of both robot-to-robot communication and peer localization is described. Section V concludes the paper with future research ideas.

II. The Khepera II Robots

The Khepera II miniature robots are compact, easy to use, use a powerful microcontroller, allow for sensor and actuator extensions and ship with free software. Such features include a Motorola 68311 25MHz processor, 512 Kbytes of flash ram for storing algorithms, two DC brushed servo motors powerful enough to speed across the table at 1 m/s or creep at 0.02 m/s, highly accurate incremental wheel rotation encoders (12 pulses per mm), built in position and velocity PID controllers, eight infrared sensors/receivers around the circumference to detect surfaces out to 100mm, and NiMH batteries for approximately 1 hour of autonomy. The dimensions of the robot measure 70mm diameter (2.75 inches) and 30mm tall (1.2 inches).

Each Khepera II weighs in at 80 grams, but can handle up to approximately 250 grams of payload in the form of extension turrets mounted to the top side. These extension turrets are a major plus in our consideration for purchasing research robots for testing control algorithms. Currently, there are a few dozen commercially-available turrets:

- Gripper (50 gram max load)
- Video camera (no onboard processing)
- Linear vision
- Matrix vision
- General I/O for simple, custom circuits
- High-speed RF wireless (2.4 GHz, 30 meter range)
- Low-speed RF wireless (433 MHz, 10 meter range)

Several turrets can be stacked upon each other with exception for the vision turrets, which are required to be at the top. Logically, these turrets will inevitably reduce the runtime of the robot, but the added functionality provided is a worthy tradeoff. In addition to the turrets listed, K-Team provides documentation for creation of custom turrets.

Software for the Khepera II is provided with the robots. A custom project environment, KTProject, is used for their whole line of robots. To compile code for embedded applications, a GNU C cross compiler is recommended and given. Also, the robots can be connected to Matlab®, SysQuake® and Labview® via plugins for remote control using a tether or one of the wireless serial turrets.

III. Vision System

The hardware testbed includes a camera in conjunction with a computer running the Fedora v1.1 operating system. An ADS Pyro FireWire™ webcam is mounted on the ceiling above the table and connected to a computer via an add-on FireWire PCI card. The output image size is 640x480 pixels at a frame rate of 30fps. When connecting across the table to the computer, a repeater is needed inline to maintain the signal.

Streaming video frames are processed in CMVision, an open source software package created by James Bruce at Carnage Mellon University [6]. The algorithm applies color-based region segmentation to the frame and outputs centroids locations. The software is composed of four main parts: a threshold classifier, a merging system to form regions using connected components, a separation and sorting system, and a top-down merging to group the regions. This process is designed to track up to 32 colors at 30 fps.

To enable tracking of a robot, a circular disk roughly the diameter of the robot is mounted to the top. Upon the disk is a unique pattern of colored dots with each disk color-set is distinct. According to recent research [16], a butterfly pattern using five color dots is an optimum layout configuration. The layout is shown in Figure 2. The central dot is unique to the robot, which provides the ID. The angle of the robot to the video reference frame is calculated as the angle between the vectors created between the like-colored dots.

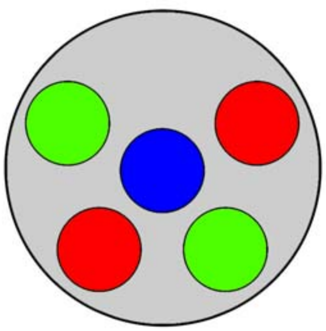

Fig 2. The butterfly pattern used to extract position and angle of the agent using the CMVision color-based classifier.

IV. Wireless Communication

To give the robots true autonomy, a wireless communication system is needed. A search of other robotic testbeds in the literature reveals that researchers are using 802.11b wireless [17] as well as standard radio frequency communication [18]. For our research, we were in need of a communication system that closely modeled communication in nature, be that either visual cues or vocalization. We hypothesized that infrared communication would yield good communication range with the ability to infer the location of other communicating robots. Evaluating our initial prototypes of infrared turrets, our hypothesis is proving to be true.

Fig 3. The Khepera II with the ARCS-designed infrared communications turret mounted to the top.

A. *Wireless Infrared Communication Khepera Turret*

The Khepera II robot's features can be easily supplemented using top-mounted extension circuits called turrets that interface to a shared extension bus. Several turrets are available for purchase through K-Team and other companies. At present, a commercial turret with peer localization was not found to exist with the exception of the vision systems, which require off-robot computer processing and custom algorithms.

For our research, due largely to budget constraints, we chose to create our own custom turret to suit our needs. An infrared communications extension turret has been built for the Khepera II robots with a maximum unidirectional transmission range of approximately ten feet (Fig 3). Communication originates on the Khepera's modified SPI bus and is buffered in the turret. The turret then packages the communication data and converts it to IrDA-specified pulses [19] that are amplified and transmitted through infrared diodes.

Data flow and sensing on the turret is governed with a Microchip 18F452 microcontroller (mcu) equipped with 32Kb of internal flash program memory, 1536 bytes of RAM, a clock speed of 40 MHz, a 10-bit ADC, several interrupts and 34 input/output pins. The mcu includes hardware UART that connects to a Microchip MCP2120, a fully-static IrDA infrared encoder/decoder.

Encoded serial data is passed to a digital potentiometer used to control the strength of the output signal from the turret. The output signal is amplified and fed into the output photo diodes. The turret uses eight infrared diodes transmitting at a wavelength of 950nm with a usable transmission cone of 30 degrees. On the flipside, seven phototransistor receivers with built-in filters are used operating at the same wavelength. Both sets are equally spaced around the perimeter of the 70mm diameter turret.

When receiving communications, the incoming signal from the photodiode is fed into a current-to-voltage amplifier. Then, a comparator produces the 0-5 Volt digital pulse signal, which is decoded by MCP 2120 into serial data. The MCP2120 UART sends the data to the microcontroller.

For each bit received, an interrupt on the microcontroller initiates an analog-to-digital conversion of the amplified infrared pulse. After the full message is received, the turret sends an interrupt to the Khepera robot indicating that there is data ready for downloading. The turret then places the data onto the modified SPI bus.

B. *Angle and Range Information from IR Communication*

A robot receiving infrared communication data can infer from the signal strengths across the array of receivers the approximate angle and range of the transmission. The raw incoming data signal is amplified, rectified and then stored in a capacitor (Fig 4). A digital output bit from the following comparator triggers an interrupt in the microprocessor, which then initiates an A/D conversion on the voltage of the signal. (Fig 5). Upon completion, the capacitor is discharged to prepare for the next receiver sampling.

IrDA infrared pulses have a specified width of 1.6ms, which is found to be an insufficient time period to sample the full array of receivers. Instead, each receiver is sampled for each successive data bit received until all seven sensors are stored. After the array is full of intensity data, the interrupt is disabled and the rest of the message is acquired as normal.

With a full array of samples, the next step is to calculate the location of the sender. This problem is broken down into polar coordinates with a calculation of the angle of transmission and a calculation of the range. The receiver sensors provide a discrete sample of the signal around the perimeter of the turret. To calculate the actual point of source, a method is needed to interpolate between the receivers. The first method to be tested is to find the centroid of the transmission "mass" across the perimeter sensors, C_θ:

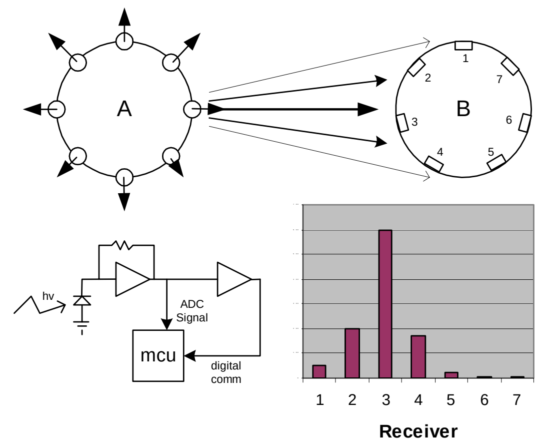

Fig 4. Calculating angle and range of communication between robots. Robot "A" transmits data to "B". Receivers 2 and 3 receive a majority of the signal.

$$C_\Theta = \frac{\sum_i signal_i * \Theta_i}{\sum signals} \qquad (1)$$

where $\theta_i = i(360)/7$, $i = 0, 1, 2, \ldots 6$ and $signal_i$ is the power level from sensor *i*.

This method would give a reasonable estimate given that the receiver sensors exhibit a linear sensitivity across the receiver's viewing angle. For a more precise calculation, the receiver network would need to be calibrated or tuned. For this, we are exploring a multi-layer, feed-forward neural network.

Once the angle is calculated the next step is to estimate the distance between two communicating robots. If all robots transmit at the same intensity, the received intensity would be proportional to the inverse square of the distance between the transmitter and receiver on two robots. In the case that the agents are free to alter their transmitting strength, the sending turret is required to insert its transmission power level (integer between 0 and 100) into the communication stream.

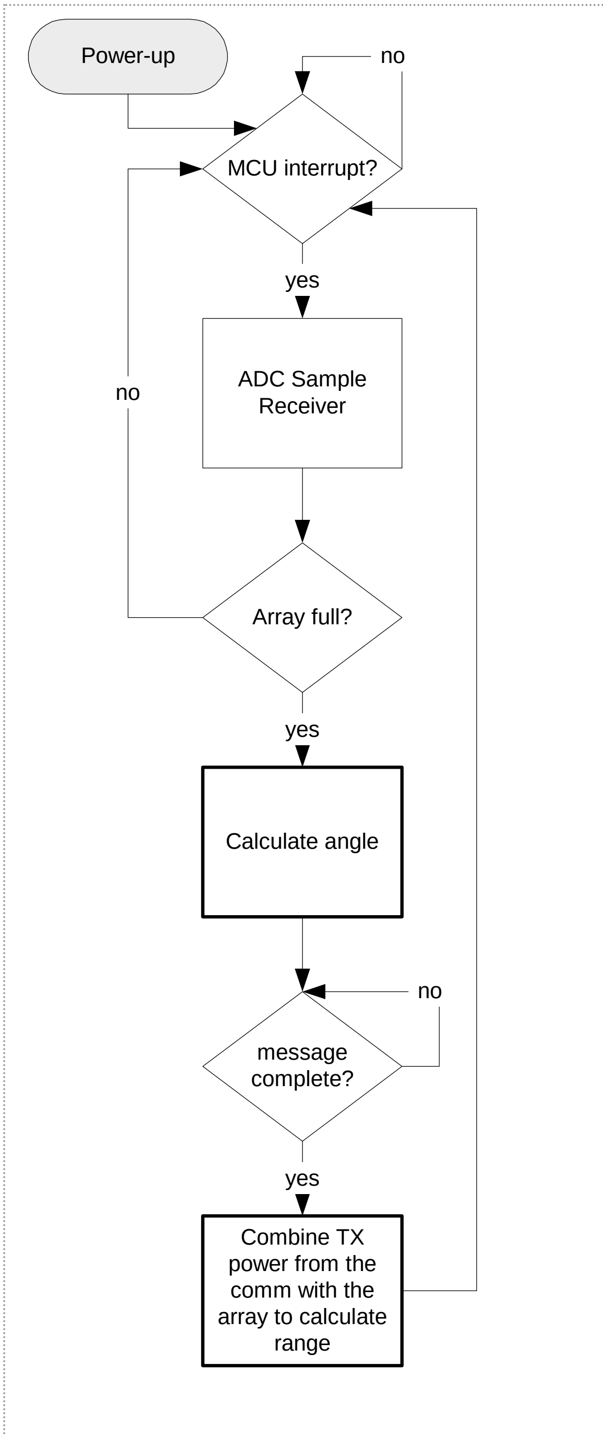

Fig 5. The process of calculating the angle and range between two communicating agents.

The receiver uses the transmission power information and correlates it to the strength of the received signal at the calculated angle. With this data the receiving turret can infer in general terms that a transmitting turret with high strength and low receiving strength is positioned "far away." Conversely, a turret transmitting with low output power and received at high strength is relatively close. For this nonlinear problem, as before with the angle calculation, we are exploring another feed-forward, multi-layered neural network.

Both neural networks (for inter-agent angle and distance calculation) are initialized with random weights to represent "no knowledge." The neural network is structured to have the normalized receiver signal array values as inputs and the inter-agent angle as an output. The overhead camera system will provide the robot with angle information with error determined by the resolution of the camera and the classifier algorithms. An error is generated between the output angle and the angle from the camera. Using standard error back-propagation techniques, the network adjusts its weights to converge on a non-linear function relating the signal inputs and the angle output.

The range calculation neural network uses the transmission power level from the sending robot, the strength of the signal inferred from the angle calculation network. The output is then compared to the range calculated by the camera system and the weights are adjusted and the process repeated until convergence.

Noise is encountered in the system when the robots are near objects such as a wall. Infrared signals reflect off these objects and interact differently with the receiving array compared to when agents communicate in the center of the table. In an attempt to reduce this noise, the built-in infrared proximity sensors are fed into the neural network in addition to the aforementioned communication strength inputs. Over the tuning period, the agent's input patterns include the walls so that the final tuning will minimize this noise. The development and implementation of these neural networks is to be the subject of a future paper.

C. Infrared Communication Protocol

At present the communication protocol is also under development. One path is using a modified IrDA stack. IrDA protocol allows for master and slave devices. A slave sits in a wait state looking for a master to initiate communications and set up a point-to-point link. An example of this would be a PDA (master) searching for a printer (slave). Only one master and slave can speak at a given time.

With seven robots on the table, each would be able to switch between master and slave depending upon their needs. Given that concurrent infrared communication from two agents will interfere, the design allows for only one master but many slaves. However, over the table, it may be the case that several pockets of agents are communicating simultaneously. This is due to their ability to moderate their communication strength via the digital potentiometer.

Another method is to synchronize the agents using the global computer system. The main computer issues a synch command several times. A window of transmission is allotted to each agent. This should minimize over-talking and data collisions, but experimentation is needed to arrive at an optimal window size.

To link with the global computer system, several infrared pods are placed at the table's edges. The pods simply convert between RS232 and IrDA signals. Agent positions, agent angles, and commands can be sent from the master computer to and from the distributed network of robots.

V. Conclusion and Future Work

This paper describes the development of a general-purpose autonomous robot testbed with Khepera II robots. The main contribution of the paper is the design of an infrared turret that can be used on the Khepera robots for robot-to-robot communication and for localization information. This new turret gives extended functionality to the Khepera robots, allowing many on-going projects to use this testbed to test theory and simulations.

The focus of future experiments will be on the learning and evolution of communication within a group of autonomous mobile robots and the coordination of movement within the same group. It is desirable that the work presented here on the testbed and communication/localization turret benefit other research efforts.

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