Design and Implementation of an Indoor Localization System for the Omnibot Omni-Directional Platform

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Abstract

The design and implementation of an indoor localization system for a novel three-degree-of-freedom omni-directional platform is presented in this paper. This localization system is a modification of the Cricket indoor localization system developed at the Massachusetts Institute of Technology (MIT). The designed system is an active beacon localization system that uses actively transmitting beacons mounted on the omni-directional platform and listeners (receivers) attached to the ceiling of the operating environment. The function of this localization system is to determine the pose of the omni-directional platform relative to a defined global coordinate system. The localization system was designed for localization of the platform in an indoor structured environment, such as a factory or office. A wireless communication link is established between the platform and a remote computer over a dedicated 802.11 b/g wireless network. The position estimates of each beacon mounted on the platform are sent from an onboard embedded controller to the remote computer over this communication link. This feedback data is then used by the remote computer to compute the platform's pose and track its motion as it travels through its workspace. Testing of the designed localization system was performed and the results are presented. These preliminary results indicate that the modified Cricket system has improved accuracy in distance and position estimation compared to the original system, with the most significant improvement in the position update rate.

Keywords: localization, active beacon system, omni-directional platform

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1 INTRODUCTION

Autonomous mobile robot navigation is the process of an autonomous robot moving from one location to another in a safe manner. The general problem of robot navigation can be described by the following three questions [1]: “Where am I?”, “Where am I going?”, and “How do I get there?”. The first question defines the problem of localization, which means determining the location of the robot relative to its environment. The second question refers to the problem of goal recognition, which is the ability of the robot to identify goals in its environment for performing various tasks. The final question defines the problem of path planning, which is the ability of the robot to find a route to reach a goal. Out of the three problems that comprise the general problem of autonomous robot navigation, the most fundamental is considered to be localization. A robot needs to know where it is located in order to decide what actions to take. For this reason, acquiring a solution to the localization problem is necessary to being able to solve the goal recognition and path planning problems. A solution to the localization problem is achieved by implementing a localization system that uses a single method or a combination of methods for location estimation.

To localize itself within its operating environment a robot requires information. The information for localization can either be a-priori information which is available to the robot before it begins navigating or information obtained from sensor measurements during navigation [2]. During navigation a robot senses its own motion and the environment around it. Measurements made by sensors that only look at the robot itself are called relative position measurements, whereas measurements made by sensing the environment are called absolute position measurements. The information obtained from sensor measurements is combined with a-priori information to estimate the robot’s position and orientation [2].

The focus of this research project is on the design and implementation of a localization system for the Omnibot omni-directional platform [3], operating in an indoor structured environment. The purpose of the localization system is to determine the pose of the omni-directional platform relative to a given global reference frame. The platform pose is defined by three variables, the x and y position coordinates and the orientation θ relative to a global coordinate system. The system to be implemented needs to be integrated with the existing systems of the omni-directional platform to provide the platform with the ability to determine its location relative to its environment.

2 BACKGROUND

Numerous methods have been developed and implemented for localizing mobile robots. The various localization methods can be categorized into two groups: relative and absolute position measurements [4, 5]. Methods that obtain information by only sensing the motion of the robot are referred to as relative position measurement methods. The process of obtaining relative measurements is known as dead-reckoning [2]. Alternatively, methods that obtain information by sensing the surrounding environment are called absolute position measurement methods. Examples of some existing localization systems implemented on mobile robots can be found in [6–11].

Relative position measurement (dead-reckoning) methods determine the robot’s location by integrating a sequence of measurements over time, which means that the current location estimate depends on previous estimates. Since location estimates are obtained by the integration of sensor measurements, this leads to the unbounded accumulation of location errors over time. Location

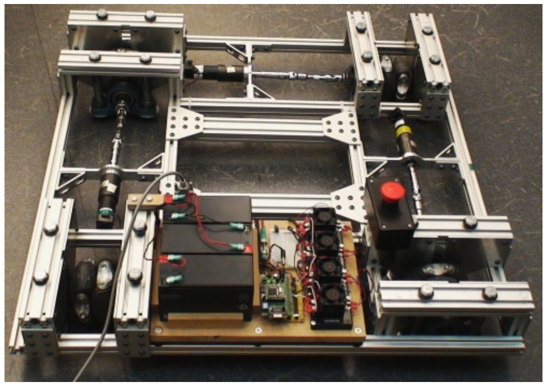

Figure 1: Omni-Directional Platform.

estimates determined from absolute position measurements are independent of any previous estimates because location is obtained from a single or a set of measurements without integrating measurements over time. Using this approach the location error does not accumulate boundlessly over time [2]. It is this latter approach that is implemented here.

3 OMNIBOT OMNI-DIRECTIONAL PLATFORM

The omni-directional platform (Figure 1), or Omnibot, for which the localization system must be implemented was built in the Mechatronic and Robotic Systems (MARS) Laboratory at the University of Ontario Institute of Technology (UOIT). The platform was built to serve as a base for a mobile manipulator which would consist of a robotic manipulator mounted on top of the platform. The design of this platform allows it to perform omni-directional travel which is the ability to travel in any direction while maintaining a fixed orientation [12]. This means that the platform can translate in any direction, rotate about a point, and perform a combination of translation and rotation simultaneously.

The structure of the platform is composed of an aluminum frame with a symmetric design. Placed at each corner of the platform is an omni-wheel, which is supported by a spring dampening system, used for absorbing vibrations that occur during motion. Each omni-wheel is driven by a DC motor through a drive shaft linkage. The motors are placed along the sides of the platform and contain digital encoders that count the revolutions of each wheel. Each motor is connected to a motor controller that controls its operation using pulse width modulation (PWM). A HC(S)12 microcontroller is used to generate the PWM signals that are used by the motor controllers for controlling the motors to achieve the desired motion of the platform. The power for all the components and systems on the omni-directional platform is supplied by an onboard power supply composed of three 12V batteries connected in parallel.

The omni-directional platform can be controlled locally through the use of a three degree-of-freedom (DOF) joystick that is interfaced with the onboard microcontroller. The joystick is used to command the platform to move in a specified direction at the desired speed. It is desired that a system be developed that will allow the platform to be controlled wirelessly from a remote computer or in an autonomous manner. In order to execute remote or autonomous control of the

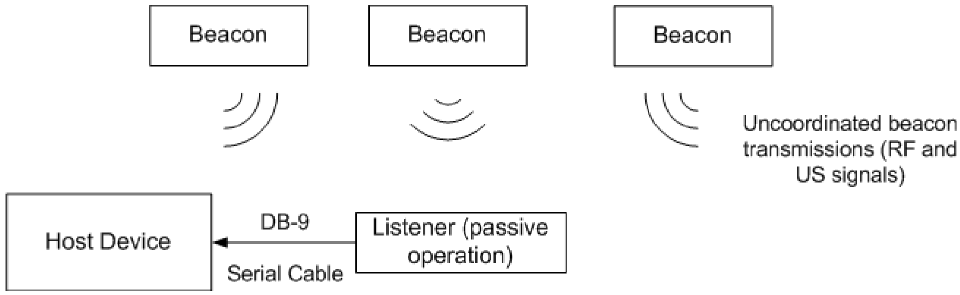

Figure 2: Original Cricket System Architecture.

platform a method is needed for obtaining the platform's pose. A wireless communication link also needs to be established between the remote computer and the platform. This will permit the transfer of feedback data to the remote computer and the transfer of control commands to the platform.

4 LOCALIZATION SYSTEM DESIGN

This section presents the design of a localization system for the omni-directional platform. This localization system is designed for the purpose of determining the pose of the omni-directional platform operating in an indoor structured environment. The pose of the platform is defined by the set of variables (x, y, θ), where x and y are the position coordinates and θ is the orientation of the platform, relative to a defined global coordinate system.

4.1 System Architecture

The design of the localization system for the omni-directional platform is based on the Cricket indoor localization system (Figure 2) developed at the Massachusetts Institute of Technology (MIT) [13]. Cricket is an active beacon localization system. The hardware used in the Cricket system consists of Cricket nodes, which are small hardware units that are configured to operate as either beacons or listeners. Cricket uses a passive mobile architecture with actively transmitting beacons placed at known positions in the operating environment. These beacons form the infrastructure of the localization system and are typically attached to the ceiling and walls of a building. Each beacon periodically transmits radio frequency (RF) and ultrasonic (US) signals. The RF signal contains beacon specific information, including the unique beacon indentification (ID) and the beacon position coordinates, whereas the ultrasonic pulse does not carry any data. One or more receivers, called listeners in the Cricket system, are attached to the object that needs to be located. The function of the listeners is to passively listen to beacon transmissions and measure the distances to those beacons using the difference of arrival times of the RF and US signals. Listeners provide the distance measurements and the information contained in the RF signals to an attached host device via DB-9 serial cables using RS-232 serial communication. The distance measurements to three nearby beacons with known coordinates are used by the host device to compute the position coordinates of the listeners with respect to the defined reference frame [13].

The localization system designed for the omni-directional platform is a modification of the Cricket indoor localization system. The modified Cricket localization system (Figure 3) uses an

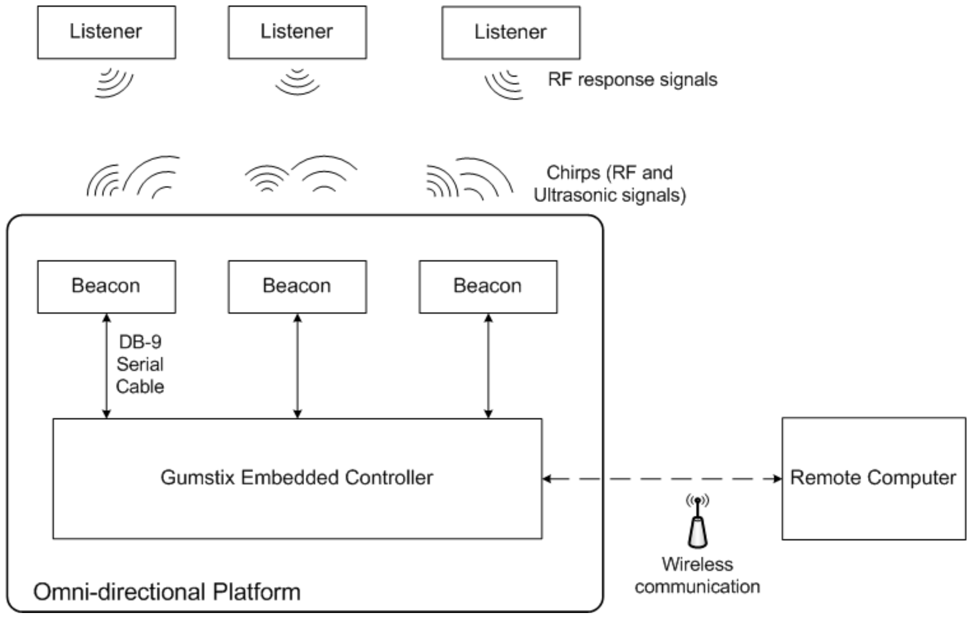

Figure 3: Modified Cricket Localization System Architecture.

active mobile architecture with listeners attached to a ceiling at known positions and three beacons mounted on the omni-directional platform. Each listener attached to the ceiling is manually assigned position coordinates with respect to the defined global reference frame. The beacons are mounted at the corners of the platform and are connected to a Gumstix embedded controller, which consists of a motherboard attached to two expansion boards. The Gumstix Connex motherboard is a single-board computer that runs the Linux operating system and is connected to the Console-vx and Wifistix expansion boards. The Gumstix communicates with the beacons using RS-232 serial communication via DB-9 serial cables connected to serial ports on the Console-vx expansion board. A wireless communication link is established between the onboard Gumstix embedded controller and a remote computer over a dedicated 802.11b/g network. Wireless protocols are used to send data between the remote computer and the Gumstix embedded controller.

4.2 Modified Cricket Localization System Operation

In the modified Cricket localization system (Figure 3) the program running on the Gumstix embedded controller sends commands to the beacons mounted on the platform using RS-232 serial communication. These commands are used to trigger each beacon to transmit signals. A beacon transmission (chirp) consists of simultaneously sending out a RF signal and a US pulse. When a beacon transmits (chirps), all the listeners that are within the ultrasonic range and have line-of-sight to the beacon will receive the signals. The listeners attached to the ceiling will first receive the RF signal and after some time interval receive the US pulse. Based on the difference in the arrival times of the RF and US signals and the propagation speeds of these signals, each listener calculates the distance to the triggered beacon. After performing the distance calculation, each listener responds by transmitting a RF signal containing the distance estimate, its ID number, and

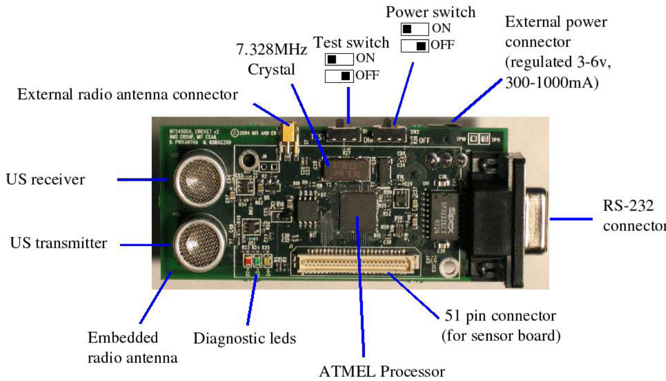

Figure 4: Cricket Node Hardware [13].

a timestamp.

The RF response signals sent from the ceiling mounted listeners are received by the triggered beacon on the omni-directional platform. The beacon transfers the data stored in the RF response signals to the onboard Gumstix embedded controller using serial communication via a serial cable. This data, consisting of distance estimates, associated listener IDs, and timestamps, is stored by the program executing on the Gumstix controller. When distance estimates to three listeners with a-priori known positions are obtained, the Gumstix program performs trilateration calculations to determine an estimate of the position coordinates of the triggered beacon with respect to the global coordinate system. The beacon position estimates are then wirelessly sent from the Gumstix controller to a remote computer over the dedicated 802.11 b/g wireless network using wireless protocols. Estimates of the position and orientation of the omni-directional platform are computed on the remote computer using the beacon position estimates and the known distances between them on the platform. This process for determining estimates of the omni-directional platform's pose is repeated continuously by the localization system.

4.3 Hardware

Cricket nodes (Figure 4) are the hardware units used for the beacons and listeners in the localization system. A Cricket node is composed of the following primary components: a microcontroller, a RF transceiver, an US transmitter and receiver, and an RS-232 interface. Each Cricket node is configured to operate as a beacon (transmitter) or listener (receiver) in the Cricket embedded software, which is written in the nesC programming language. The Cricket software runs in the TinyOS embedded operating system [14]. The signals transmitted by beacons travel in a 40° cone shaped propagation pattern. The maximum range of the ultrasonic signals is 10.5 m when there are no obstacles between the listener and the beacon and they are facing each other [14].

A programming board is used to upload software onto the Cricket hardware units. The model numbers for the Cricket nodes and programming board are MCS410CA and MIB510CA, respectively. The Cricket nodes can be powered using two standard AA batteries or with an external power supply that provides 3V-6V DC at 300-1000mA, through the external power connector [14].

The Gumstix embedded controller (Figure 5) used in the localization system is a hardware unit

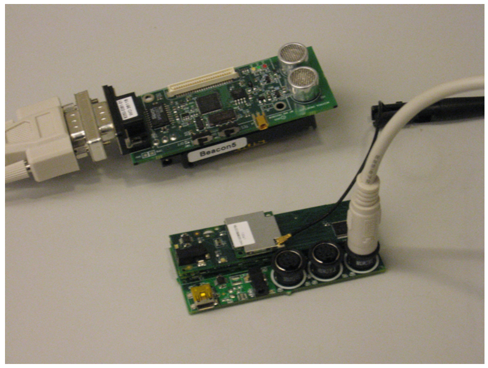

Figure 5: Gumstix Hardware.

that is composed of a Connex motherboard connected to the Console-vx and Wifistix expansion boards. The Connex motherboard is a single-board computer that runs the Linux operating system. The Gumstix program used in the localization system runs on the Connex motherboard. The Console-vx expansion board has three RS-232 serial ports to which the three beacons on the platform are connected via DB-9 cables. The Wifistix expansion board provides wireless connectivity for the Gumstix. Wireless communication between the Gumstix embedded controller and a remote computer is performed over a dedicated 802.11b/g network using wireless protocols. The Gumstix hardware unit is powered using an external power supply that provides 3.5V-5V DC, through a power jack on the Gumstix [15].

5 IMPLEMENTATION OF THE LOCALIZATION SYSTEM

5.1 Cricket Node Software

The Cricket localization system uses TinyOS 1.x. This is an operating system specifically designed for use with embedded sensor networks. The operating system minimizes power consumption by using an event-driven C-based programming language called nesC. Due to the nature of the language, applications can be built by wiring together separate, pre-existing applications (called modules). This type of approach also minimizes code size, which is another benefit in embedded sensor networks.

The same code is used for both the listeners and the beacons. This allows a Cricket node to be configured as either a beacon or a listener, and makes it easy to switch the mode without reprogramming. The software is composed of six primary events, shown in Figures 6 and 7: *Sending Radio Signal*, *Receiving Radio Signal*, *Ultrasound Detected*, *Serial Send*, *Receiving Serial Data*, and *Ultrasound Send*. The rest of the code is associated with initialization, hardware drivers, communication protocols, and other low level programming. Whenever one of the six events occurs, a series of commands is executed. The way a Cricket node responds to a firing of an event depends on whether it is configured as a beacon or a listener.

On a beacon, when the *Receiving Radio Signal* event is triggered, this means that a distance report from a listener has been received. The *Serial Send* function is then called, and the distance report is sent to the beacon's serial port. On a listener, if the *Receiving Radio Signal* event is

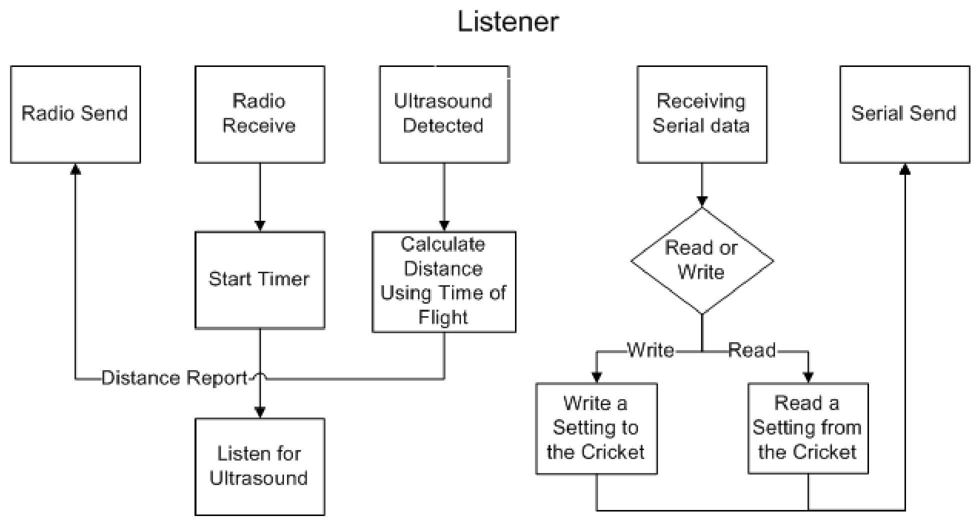

Figure 6: Listener Events Diagram.

triggered, a timer is started so that the flight time of the US signal can be obtained. The *Ultrasound Detected* event in a listener stops the timer, and calculates the distance to the beacon from which the signal originated. On a beacon, the *Ultrasound Detected* event does nothing. On a listener, the *Serial Send* event just gives the user feedback during configuration, and on a beacon the event is used to relay distance report information received from the radio. The *Ultrasound Send* event is only used by the beacons.

5.2 Gumstix Embedded Controller Software

The Gumstix embedded controller used in the localization system executes a software program written in the C programming language. This program was developed on a computer running a Linux operating system using a cross-compilation toolchain. Using this toolchain the program code was compiled on the Linux development machine and then transferred to the Gumstix controller for execution.

The structure and operation of the software program implemented on the Gumstix controller is shown in Figure 8. At the start of execution, the program initializes the serial communication (COM) ports on the Console-vx expansion board. These serial COM ports are used in the system to interface the Gumstix controller with the platform mounted beacons using serial DB-9 cables. Each of the three COM ports is enabled and configured by setting the values of all the required parameters for serial communication, such as the baud rate. The program then commands a particular beacon to chirp, by sending the string ‘p ch’ to one of the Gumstix’s serial ports. The beacon connected to the serial port to which the message was sent is triggered and simultaneously transmits a RF signal and a US pulse. Listeners that detect the triggered beacon’s transmission calculate estimates of the distance to that beacon and report the values back in RF messages along with their IDs. The triggered beacon on the platform receives these RF response signals and sends the data contained in the messages to the Gumstix controller using serial communication.

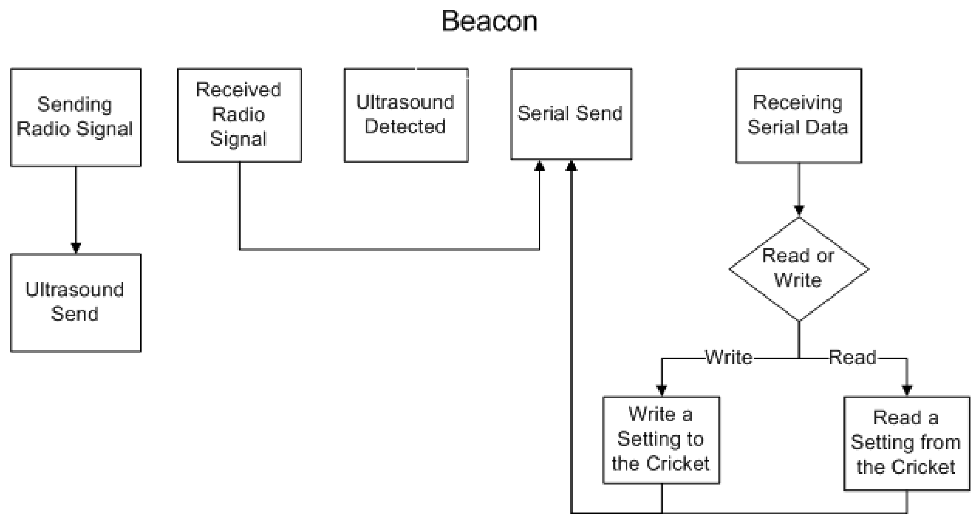

Figure 7: Beacon Events Diagram.

The Gumstix program reads the serial port to which the triggered beacon is connected and obtains the string of listener response messages. Contained within this string are the distance estimates, listener IDs, and timestamps provided by all the listeners that detected the triggered beacon's transmission. The data contained in the listener response messages is then parsed by the program. The distance estimate values and the associated listener IDs are converted from ASCII to type double and integer, respectively, and the converted values are stored in two separate arrays. After parsing the data, the distance values are arranged in a specific order and trilateration calculations are performed to determine the x and y position coordinates of the triggered beacon with respect to the defined global coordinate system. These calculations use distance estimates to three ceiling mounted listeners fixed at known positions within the global reference frame. The equations used for trilateration are:

$$x = \frac{r_1^2 - r_2^2 + X_2^2}{2X_2} \tag{1}$$

$$y = \frac{r_1^2 - r_3^2 + x^2 + (x - X_3)^2 + Y_3^2}{2Y_3} \tag{2}$$

where, x and y are the position coordinates of the beacon, r_i is the distance estimate to listener i, and X_i and Y_i are the x and y coordinates of listener i, respectively. The calculated beacon position estimates are then sent to a remote computer over the wireless network. This process for determining the position estimates of beacons is continuously performed by the Gumstix program by successively triggering each connected beacon.

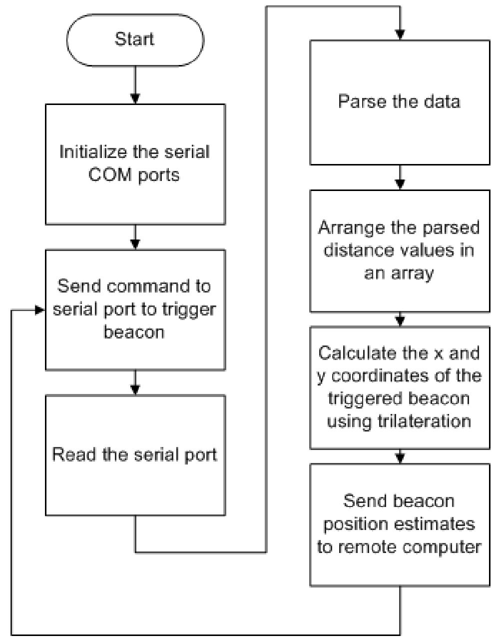

Figure 8: Gumstix Embedded Controller Program Flowchart.

6 Testing and Results

Tests were conducted to verify that the modified Cricket localization system still had the accuracy of the original Cricket system. This was done by placing a Cricket beacon connected to a PC on the ground, aimed horizontally, and placing a listener a measured distance away. The beacon was commanded to chirp by the user, and the distances recorded. The resulting data is shown in Figure 9.

The standard deviation of the error from the actual value is 5.7389. After various trend-lines were fit to the data, it was determined that a linear function results in the lowest standard deviation. After applying the correction given by the equation from the trend-line, the standard deviation was reduced to 0.9984. The average of the absolute value of the errors, before correction, is 33.49 cm, and the average of the absolute value of the errors, after correcting with the function of the trend-line is 0.7343 cm.

In the original Cricket system developed at MIT the distance and position estimation accuracy was reported to be 5 cm and 10 cm, respectively [13]. From preliminary testing of the modified Cricket system it was determined that the modified implementation has better distance and position estimation accuracy than the original system. Most notably, the position update rate has been improved considerably over the original implementation. This improvement is due to the change in architecture from a passive mobile system to an active mobile system.

7 Future Works

Now that the feasibility of the system has been demonstrated, the next step is to scale it up. Currently, three listeners are being used to determine the position of the beacons. To expand the

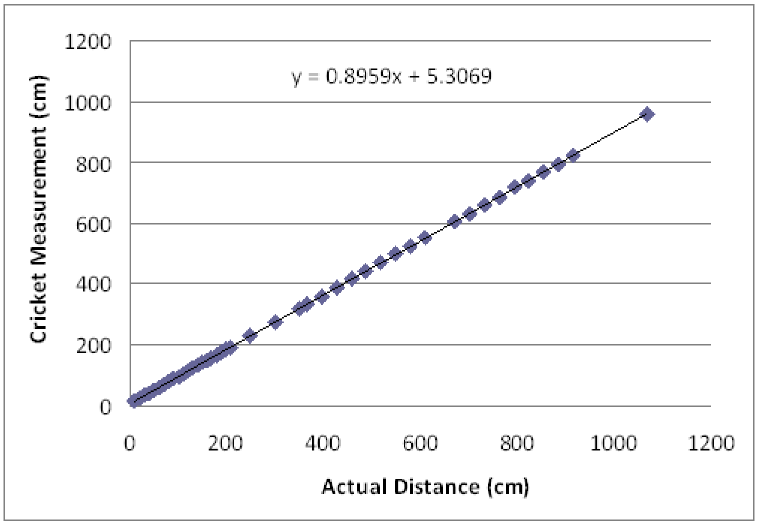

Figure 9: Cricket Distance Estimation Test.

coverage beyond that of the three listeners, the code algorithm must be expanded. In addition to scaling the system, a secondary system for localizing the omni-directional platform will be implemented. This secondary localization system will employ odometry to produce location estimates using the encoder data from the digital encoders contained in the drive motors of the platform. The location estimates from the modified Cricket system will be combined with those from odometry to produce improved estimates. In addition, the possibility of using a Kalman filter to increase the accuracy and reliability of the location estimates will be explored.

8 Conclusions

This paper has presented the design of an indoor localization system for the Omnibot omni-directional platform. This localization system was designed by modifying and adapting the Cricket indoor localization system, originally developed at MIT. The modified Cricket system is an active beacon localization system which uses listeners attached to a ceiling as the external references. Three beacons are mounted on the omni-directional platform and are interfaced to a Gumstix embedded controller. The localization system determines the position estimates of the beacons and sends these values to a remote computer over a wireless communication link. The pose of the Omnibot platform is then computed on the remote computer using the received position estimates.

The development of the localization system is currently ongoing and further work will be done to add additional functionality. Testing of the modified Cricket system at this stage of development was performed and the preliminary results have shown that the modified implementation provides improved performance over the original Cricket system. Additional testing of the localization system will be performed in future work, as more functionality is added to the system.

9 ACKNOWLEDGEMENTS

The authors wish to thank the Natural Sciences and Engineering Research Council (NSERC) of Canada, the Canada Foundation for Innovation (CFI), and Cameco Corporation (through the Cameco Research Chair in Nuclear Fuel at UOIT) for providing funding to support this research.

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