Smart Stool for Assistive Living Model-Based Design

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***Abstract*—There is an increasing concern in elderly living alone and the dangers associated with this. For this reason, there is a desire to assist the living at home for the elderly with smart materials, smart systems called Cyber Physical Systems. Research has focused on designs that will help the elderly to live in a safer and better environment. This project presents a device that will assist the elderly in helping move a stool near the desire location. The model-based design concept of this course will allow to model and simulate the protoype before building, allowing to understand the feasibility of this project.**

I. Background

A. Smart Systems

Smart systems generally consists of diverse components like sensors, elements transmitting the information to the command-and-control unit, components transmitting decisions and instructions, actuators that perform or trigger the required action. Smart systems are devices that incorporate functions of sensing, actuation, and control in order to describe and analyze a situation, and make decisions, thereby performing smart actions. In most cases the smartness of the system can be attributed to autonomous operation based on closed loop control, energy efficiency, and networking capabilities. The requirement of the smart system is high degree of reliability, efficient and sustainability, damage detection and self recovery, Intelligent operational management system. Smart materials can be broadly classified into materials like piezoelectric, magnetostrictive. electrostrictive, shape memory alloys, optical fibers and materials with added functions to detect certain signals [2].

B. Cyber Physical System

Cyber-physical systems (CPS) are engineered systems that are built from and depend upon the synergy of computational and physical components [3]. Few examples are Sensor-actuator networks, intelligent transport system, Robotics etc. There are many challenges while designing a CPS such as real time constrains, robustness, integration, scalability, security and so on. CPSs integrate computation, networking and physical dynamics [4]. Many parallel processes constitutes a physical process. Physical dynamics involves measuring and controlling the dynamics of these processes. The design of CPS requires understanding of computers, software, communication and physical processes.

C. Elderly Ageing at Home

The association between social isolation and mortality remained strong after demographic factors and baseline health and mobility had been taken into account in multivariable models [5]. There is a major shift in the population towards old ages in every country of the world. Due to their higher dependency ratio [6], this is a major problem in many countries. So its a necessity that we must develop such a smart system that supports elderly for an ambient living environment.

D. Ambient Assisted Living

One of the research goals in the context of Ambient Assisted Living (AAL) concerns the integration of new technologies with the social environment to support people in their daily activities and increase their quality of life [7]. The goal of our CPS is to develop the core system science needed to engineer complex cyber-physical systems upon which people can depend with high confidence. The main focus of these projects is to develop technological platforms that allow a natural and pleasant interaction with a smart environment, by implementing an easy access to its services

II. Problem Statement

Elderly people cannot lift and move a stool at the same time, despite desiring a stool for a variety of purposes including object placement, seating, or use as a footrest. Stools serve as an extension to people which provides them flexibility, increases comfort, and supports them. It is important to help the elderly in improving their quality of life.

III. Model of Physical Processes

A. Mobile Platform

Fig. 1. Turtlebot platform developed by Willowgarage Robotics as an Open Development Platform [9]

The smart stool will be located indoors, typically in the living room of an elderly person. Therefore, we fix a coordinate frame to the robot where the x-axis and y-axis are tangential and normal to the wheel drive, respectively. As the robot has two wheels, the system can be modeled as a differential drive, where each wheel is actuated independently allowing it to move and rotate in place.

$$v_o = \frac{\left(\dot{\phi}_r + \dot{\phi}_l\right) r}{2} \tag{1}$$

$\mathbf{v}_c$ is the speed of the center of mass of the robot in the robot coordinates. Equation (10) denotes the speed of each wheel $\dot{\phi}_r$ and $\dot{\phi}_l$ and the radius of the wheel radius r.

$$\mathbf{v}_c = \mathbf{v}_o + \mathbf{d} \times \omega \tag{2}$$

$$\omega_c = \omega_0 = \dot{\theta} = \frac{\left(\dot{\phi}_r + \dot{\phi}_l\right) r}{2b} \tag{3}$$

The dynamics of the system can be found using the Euler-Lagrange theorem of nonholonomic systems.

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\mathbf{q}}}\right)^T - \left(\frac{\partial L}{\partial \mathbf{q}}\right)^T = \mathbf{S}(\mathbf{q})\tau + \mathbf{A}(\mathbf{q})\lambda \tag{4}$$

Where for the mobile differential drive robot we have

$$\mathbf{S}(\mathbf{q}) = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}; \tau = \begin{bmatrix} \tau_r \\ \tau_l \end{bmatrix}; \mathbf{q} = \begin{bmatrix} x \\ y \\ \theta \\ \phi_r \\ \phi_l \end{bmatrix} \tag{5}$$

We know that the Lagrangian is the difference between the Kinetic and Potential Energy of the system. As a mobile robot is restricted to a horizontal plane, the Potential Energy is 0. Then,

$$L = KE = \frac{1}{2} m_r {v_c}^2 + \frac{1}{2} I_r \dot{\theta}^2 + \frac{1}{2} I_w \dot{\phi}_r^2 + \frac{1}{2} I_w \dot{\phi}_l^2 \tag{6}$$

Equation (6) requires to substitute v_c with the world coordinate systems x and y.

$$v_c^2 = \dot{x}^2 + \dot{y}^2 - 2d\sin(\theta)\dot{x}\dot{\theta} + 2d\cos(\theta)\dot{x}\dot{\theta} + \dot{\theta}^2 d^2$$

$$\dot{\theta}^2 = \frac{\left(\dot{\phi}_r + \dot{\phi}_l\right)^2 r^2}{4b^2}$$

The state space reduced model can be found by solving for $\dot{\mathbf{q}}$ and $\dot{\mathbf{v}}$

$$\dot{\mathbf{q}} = \mathbf{G}(\mathbf{q})\mathbf{v} \tag{7}$$

$$\dot{\mathbf{v}} = -\mathbf{M}^{-1}(\mathbf{q})\mathbf{m}(\mathbf{q},\mathbf{v}) + \mathbf{M^{-1}}(\mathbf{q})\mathbf{G^T}(\mathbf{q})\mathbf{S}(\mathbf{q})\tau \tag{8}$$

IV. Localization

The Estimote Beacons, as seen in Figure 2, are small wireless sensors that can attach to any location or object. They broadcast using Blueetoth LE to provide indoor location features such as proximity-gate functionality, context aware, temperature and motion. The Estimotes transmit important information through bluetooth such as the UUID (Universally unique identifier), Major, Minor and RSSI (Received signal strength indicator). The UUID

Fig. 2. Estimote Beacon used on the smart environment for localization based on the bluetooth low energy signal

is a 128-bit value that is defined by the MAC address. The major is used to group related sets of beacons, while the minor is used to identify a beacon within a group. The RSSI value is the signal strength in decibels between the receiver and the beacon. Our project cares about the MAC address and the RSSI value of the beacon. The estimotes are calibrated to have an RSSI value at 1 meter, which is called Tx Power. This variable is used for localization calculations.

The smart environment will have 6 Estimotes in known positions across the room. In order to calculate the distance between the receiver and the beacon, the Log-distance loss path model is used. This model proposes that the signal strength decreases as the distance increases due to signal propagation, interference, and line of sight. The loss path model is given by the following equation:

$$L = 10n \log_{10} d + C \tag{9}$$

Where the n is the loss path exponent. n varies according to the signal frequency, the environment, and the type of obstacles and intereference that can occur in the room. For a small office room, with soft divisions, we will use $n = 2.6$. L is the RSSI value of the sensor at a given time. Figure 3 displays the RSSI value as distance increases. d is the distance between the beacon and the receiver. Finally, C is the TX Power value used for calibration of the Estimote at 1 meter. We then proceed to calculate the distance between the Estimotes and the Galileo.

$$r_1^2 = x^2 + y^2 + z^2 \tag{10}$$

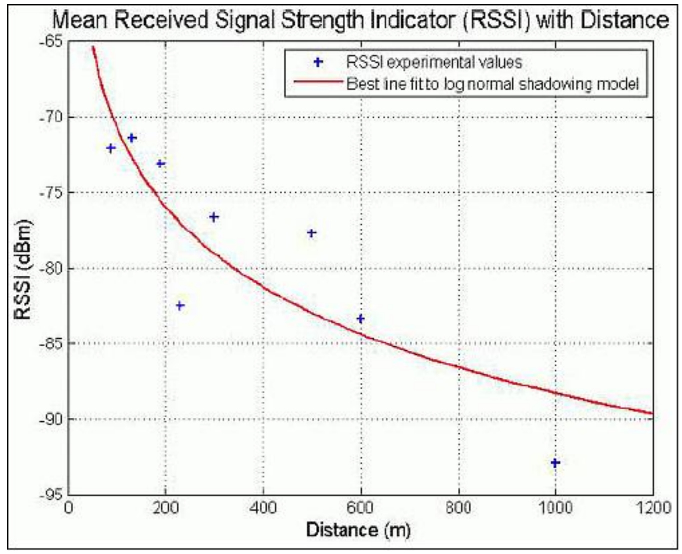

Fig. 3. RSSI test for distances between 0 and 10 meters.

$$r_2^2 = (x-d)^2 + y^2 + z^2 \tag{11}$$

$$r_3^2 = (x-i)^2 + (y-j)^2 + z^2 \tag{12}$$

From Equation (10) and (11) we obtain:

$$x = \frac{r_1^2 - r_2^2 + d^2}{2d} \tag{13}$$

Assuming that the first two spheres intersect in more than one point, that is that

$$d - r_1 < r_2 < d + r_1 \tag{14}$$

Therefore, we substitute Equation (13) into the first sphere to produce the equation for a circle, the solution for the first two spheres is:

$$y^2 + z^2 = r_1^2 - \frac{(r_1^2 - r_2^2 + d^2)^2}{4d^2} \tag{15}$$

Substituting $z^2 = r_1^2 - x^2 - y^2$ into the formula for the third sphere and solving for y we obtain:

$$y = \frac{r_1^2 - r_3^2 - x^2 + (x-i)^2 + j^2}{2j} \tag{16}$$

Now that we have the x and y coordinate of the solution point, we can simply rearrange the formula for the first sphere to find the z component:

$$7 \tag{17}$$

After obtaining the distances between transmitter and receiver, we take the lowest three distances. With only three points, we use trilateration to localize the Galileo in the room. The process of trilateration can be seen in Figure 4.

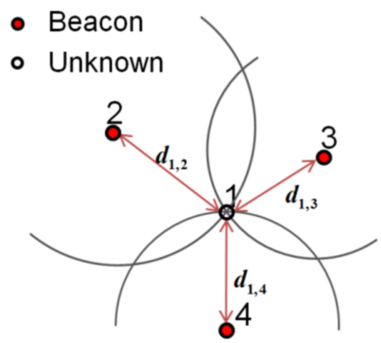

Fig. 4. Trilateration setup of concurring spheres

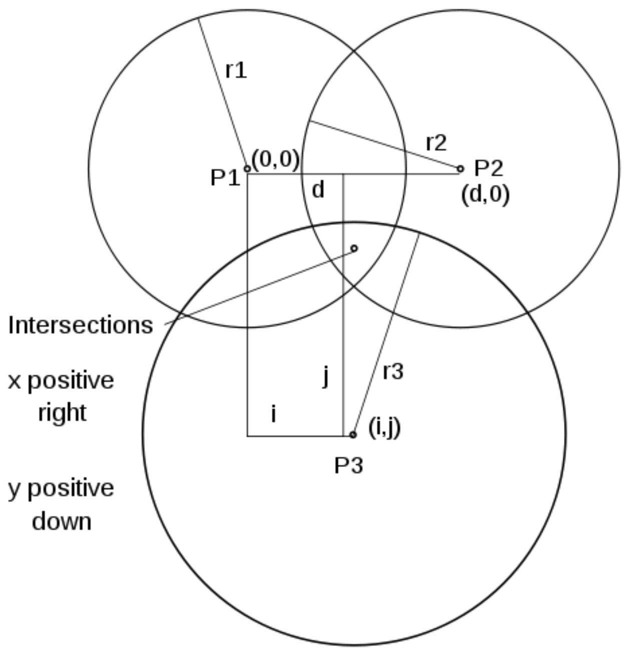

Fig. 5. Trilateration equations for localization of estimotes in smart environment

V. CHARACTERIZATION OF THE PROBLEM

We have not constrained the rate at which the robot must move through the living room. The rate of the robot is an adjustable parameter. Each wheel can be actuated independently, and the ratio of their rates is a controllable parameter. Each wheel can rotate up to $\pm v_{max}$, where $v_{max} = 0.65$ m/s. The turtlebot has encoders for position measurement and velocity estimation. It also possess a gyroscope for rotational velocity. For object avoidance, LIDAR sensors and embedded stereoscopic camera can be used for self-navigation and localization in the environment. Embedded drop wheels are going to be used as interrupts to detect when one of the wheels is not in touch with the ground or detect cliffs.

A data management system should be implemented in order to create and maintain a priority queue that will rank tasks based on urgency. Secondary tasks will be performed only if the user is not currently using or in need of the smart stool. Time perception can be useful to perform several secondary tasks when it knows users are not in need of the smart stool, for example not being at home, or asleep.

VI. APPROACH

The Smart Stool is assumed to be able to autonomously navigate a path, and being able to localize itself in the environment. Navigation and localization can be done by the robot itself or by means of external sensor data, such as Estimote Beacons or Stickers, or a Smart Floor. Depending on the priority level of the task, the robot could either autonomously perform such task, or be able to accept user input. The primary task of the robot will be to fulfill explicit user requests such as being used as a stool, or moving to a desired location. Secondary Tasks that the robot will perform will include but not limited to retrieving the mail, chase pets or clear a path, and checking floor uniformity. All these tasks can be performed autonomously. Data gathered from these tasks will be relayed to other smart systems in the house. While primary tasks will take effect above secondary tasks, the user can dismiss the robot such that a secondary task can be completed. By receiving user input, the stool can be trained through a supervised learning environment. For example, if the robot is in the general location but the user requires a slightly different position, the user is capable of adjusting the robots position. This position can then be learned by the robot in order to complete the same task in the future, with reduced user input.

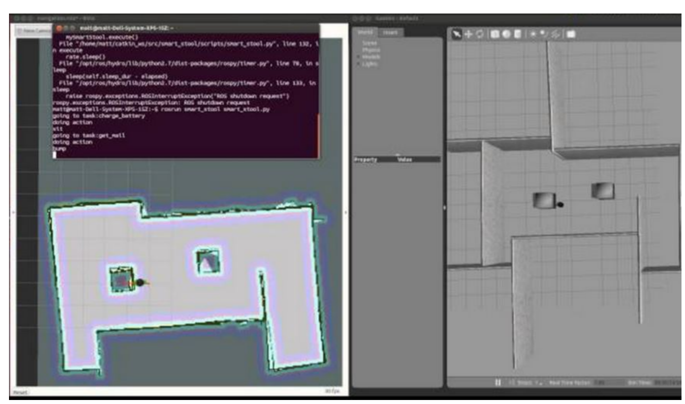

Fig. 6. Gazebo simulation model of the Smart Stool and a smart environment, while the Smart Stool performs repetitive tasks.

In order to minimize the effort required by the user to operate the stool, all input that will be required is a summon command and a dismiss command. The summon command will tell the smart stool to approach, and the dismiss command would send the smart stool to its designated storage location that is out of the way of general household activities. To navigate autonomously, the smart stool will need a vision or object detection system. In order to accomplish all of these tasks, we will use a Turtlebot to simulate a smart stool. The Turtlebot incorporates the vision and obstacle detection systems required for the functionality of the system.

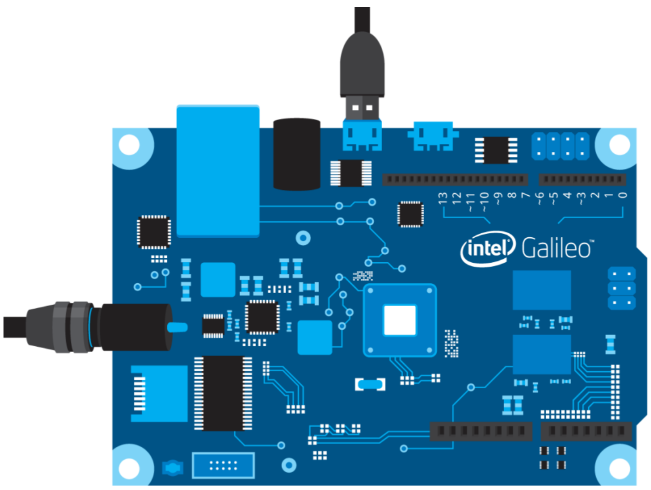

Fig. 7. Intel Galileo-Board with Quark-Processor [10]

This Intel Galileo would be used to send the summon and dismiss signals to the Turtlebot. A button attached to the Intel Galileo would accomplish this. Additionally, the Turtlebot can send status updates, location information, and estimated time of arrival information to the user in order to keep the user informed. The Turtlebot will be equipped with area mapping software in order to determine its current location and to plan a path to the user's requested position based on a known area map. The user's position will be determined using the Estimote sensors in the equipped smart environment. Once the user's position is determined, the position will be sent from the Intel Galileo board to the Turtlebot so the Turtlebot knows where its target location is.

Once the Smart Stool has navigated to the vicinity of the requested summon position, the user can input fine-tuning control via a four-direction control pad found on the controller which can be seen in Figure 8.

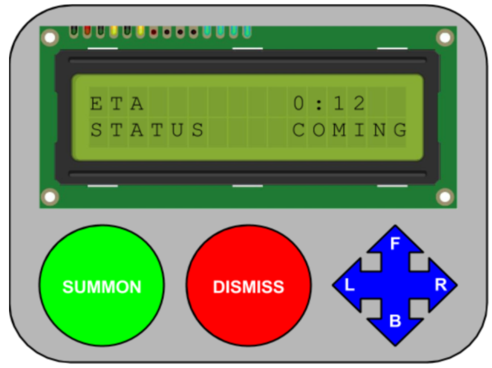

Fig. 8. Controller Interface for Smart Stool including D-Pad, Buttons and LCD

Once the user has gotten the robot to a desired position using this fine control capability, the user will stop sending control inputs and the Smart Stool will log this position along with relevant state information for future reference. For example, next time the user summons the Smart Stool to a similar location at a similar time of day, the smart stool will go to the previous fine-tuned position, rather than the initial positional approach attempt. Over the course of many iterations, a complete distribution of exact locations versus time and day can be generated, stored, and analyzed, allowing the Smart Stool to be very predictive and eventually reduce the amount of user input needed to a minimal value or zero.

VII. Control Algorithms

The figure shows the implementation of two-wheeled differential drive robot using ROS package. A virtual joystick is provided to the user to send manual signal to the robot for fine adjustment. Thee manual signals override the autonomous operation and the controller comes into action just to transmit the signal to the left and right wheels. No feedback control action takes place during manual fine adjustment. The controller gets the sensor information from lwheel and rwheel which acts as a feedback. These are wheel encoders and the transmitting message should be the number of ticks received in each wheel. The controller employed is a PID controller. PID controller has the optimum control dynamics including zero steady state error, fast response (short rise time), no oscillations and higher stability. Consider s as the linear velocity and θ is the angular velocity and they are measurable. The PID control action can be performed based on the following block diagram.

VIII. METHODS OF COMPUTATION

The system will interact with external sensors and arrays in order to provide information for the Smart Stool. The system's computation method, as seen in Figure 9, will involve cascaded finite state machines and priority queues in order to select tasks. Primary Tasks, as seen before, are able to learn from the user's input. Every tasks will have the same method of computation by selecting the desired sensor input and prioritizing every task. By doing this, the robot can autonomously be capable of selecting what it will do without user input. Each additional secondary task is independent of each other; therefore, it is easy to incorporate additional tasks as time goes on per request of the user or based on additional sensors.

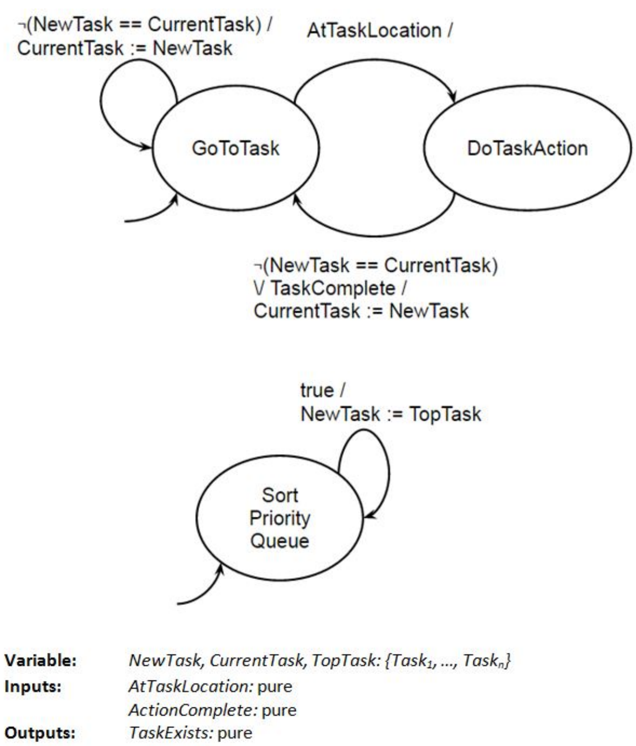

Fig. 9. Finite State Machine for the Smart Stool system including a priority queue as a task list

Our model of computation includes two finite state machine that determines the task that the Smart Stool should perform and in what order. The first state machine is a priority queue list that will tell the Smart Stool which task should be performed. Figure 1 shows the priority queue and updates every time the top task changes.

The next finite state machine controls the current action of the Smart Stool. When the Smart Stool reaches the desired location, it will perform the action required. But whenever the priority queue seen in Figure 1 updates the task, the Smart Stool will perform the new task associated with it. Figure 9 shows the Smart Stools finite state machine to perform the task. Each task has an associated location, action, priority, and activity. As the priority of the action changes, it will be reflected on the FSM. Likewise, in the bottom section of Figure 9, the Smart Stool will go to the desired location and perform the desired action for the current task. Example of tasks include charging, stool function, get mail, and chasing pets. For example, the location for get mail will be the door, while the action is to retrieve mail, and the priority can be changed to high when the mail arrives.

One of the tasks requires the user to be located in the smart environment. To do this, estimote sensors are used to localize the user based on the BLE RSSI values. Using trilateration, the position of the user is estimated. For all these computations, we are assuming the robot is always localized on the environment due to the ROS SLAM and MCL packages. We are assuming that the Smart Stool is able to locate and avoid obstacles based on the ROS packages implemented and are beyond the scope of this project.

IX. VERIFICATION AND VALIDATION

In order to verify and validate that the Smart Stool is able to complete all the tasks we proposed, several components need to be tested and validate their results. The first test that we ran to verify the localization of the user using the Estimote Sensors was to calibrate the Estimote at 1 meter away from the receiver. The RSSI at 1 meter is a calibrated data point that will be used to calculate the distance of the Estimote. Next, the Smart Stool needs to be tested to make sure the connectivitiy between the Galileo and the Turtlebot are adequate. Otherwise the system would not be able to receive the commands, tasks, and summon or dismiss signals. To validate our simulation model

From the test and verification, we validated that our system is able to:

- To execute tasks that will reduce the amount of menial work that the elderly need to do and reduce safety risks.
- To localize in the Smart Environment with Estimote Sensors and find the user

- To send status information such as the estimated time of arrival (ETA) and current task, to the user wirelessly.

X. Conclusion

The Smart Stool is able to reduce the problems and dangers associated with living alone for the elderly. The need of a Smart Stool allows the elderly to improve their comfort, provide flexibility, and support their life. It was important to help the elderly improve their quality of life. This project was able to successfully navigate through the smart environment performing given tasks while being summoned and dismissed by the user at request. The use of the Estimotes as localization devices are great for indoor localization and near signal fields. As the estimotes get further apart, the signal drops logarithmically, therefore making it more difficult to localize the user accurately. For future works, the Smart Stool should be able to adaptively modify the pre established map in order to locate new features, obstacles or movement in the environment. This will give the other smart objects a good picture of objects along the environment. Additionally, the Smart Stool would benefit by receiving localization coordinates of different methods such as wearables, or a Smart rug. This way, the Smart Stool could predictively reach a certain location or perform a certain task depending on the user's current trend. More importantly, the system is able to successfully locate, navigate, and localize a user and perform tasks associated with a smart environment. This increases the elderly living standard as it allows the user to have a personal stool to increase flexibility, and improve their comfort.

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