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Model-Based Approach for Cyber-Physical Systems Applications Development

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Model-Based Approach for Cyber-Physical Systems Applications Development

Completed Research Paper

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Abstract

Design and development of Cyber-Physical systems (CPS) are challenging due to their computational and physical dynamics. However, while studies investigated on model-driven approaches in other information system domains, research concerning how to support CPS design and development using modelling approaches and tools, is limited. Our research shows how model-based approaches and tools can be used to model scenarios in CPS application development while ensuring the CPS dynamism remains intact. We present a model followed by a prototype as an artefact to show a CPS design for health related monitoring. The paper introduces AutoWheel, an automatic wheelchair based monitoring system, as a case study for our design. The proposed design focuses on modeling the system and verifying the behavior of its working in the given mobility related health scenarios. The motivation of the AutoWheel project arises from the need for building low cost manageable technological interface and information system especially for the people in developing countries.

Keywords: Cyber-Physical Systems, Modeling, Prototype, Health Scenarios.

Introduction

Advancement in computer, network and sensory technologies have given rise to the emergence of the Fourth Industrial Revolution. CPS is one of the technologies which has been built on the foundation of cross-disciplinary domains such as embedded systems and network technologies and has increasingly become part of the Industry 4.0 revolution (Gruettner et al. 2017). CPS illustrated as the closed integration of computational units, communication, and control of the physical components. Hence, the design and architectural requirements, i.e., safety, reliability, modularity, interoperability, and verification, are more stringent in CPS architectural design than traditional software or embedded systems (Lee 2015; Syed et al. 2015). However, despite the wide range of tools and methods to date, are proposed and used in other CPS applications, designing high-confidence CPS such the CPS applications in the health domain, is a research direction yet to be thoroughly explored.

Additionally, applications of CPS in medical and health domain are posing challenges in term of design primarily due to their safety and continuous monitoring nature. In this context, research studies have been advocating Model-based approaches which help to abstract complex behavioral aspects of the system and provide an adequate foundation to design the CPS applications (Lee 2008). However, CPS architecture requires different tools and techniques which can model individual components and physical processes to serve the need for heterogeneity and dynamism of system behaviors (Mikusz 2015).

Our research unravels three aspects:

- First, to understand the socio-technical challenge in the given environment.
- Second, to investigate how the model-based approach and tools can be applied to incorporate these challenges in CPS architecture design requirement. Applicability of the approach is proved by modeling health related scenarios essential in wheelchair mobility. We exhibit this by incorporating Safety scenarios in our model and subsequently verified the scenarios using a time-constraint based tool.
- Third, to understand how to build a solution in term of hardware implementation and deployment which support the developed model and to verify it. To this end, we used low-cost Commercial off-the-shelf (COTS) components and familiar technological interface in our design.

The paper is organized as follows. Section "Background" provides some necessary background on the importance of model-based approaches for CPS design, especially for the healthcare domain, a socio-technical challenge with existing wheelchair control and navigation systems. Section "System Overview" describes the system's architectural view – the highest level of abstraction; participating components and their control flow. Section "System Model" explains the model by taking a safety scenario as an example to demonstrate how individual scenarios can be modelled in CPS design, followed by a state machine based verification technique to verify the developed model. Section "Prototype Implementation" is an instantiation of the artefact. Section "Our Findings and Limitations" outlines how the model-based approach helps to design and implement individual scenarios for health related CPS application development, what lessons we have learned and limitations of the current work. Finally, Section "Conclusion and Future Work" concludes the paper and highlights the research challenges to be addressed for wheelchair based monitoring systems and its physical deployment.

Background

1. Model-based approach

Recent advancements in modeling tools help us to design and model applications considering the non-functional aspect of the system, i.e., safety, security and reliability which are the critical quality attributes for every CPS application development (Syed et al. 2015). Existing approaches for model-based design such as AADL, UML, SysML, meta-models and their combination with modeling tools such as Simulink, ACME studio, and formal verification techniques, have been used and applied to various applications and information system domains (Rajhans et al. 2009; Feldmann et al. 2013; Shanaa et al. 2017). These tool and techniques have been used in the versatile domain from business modeling, process modeling to information modeling; or used in new technologies to represent the various aspect of the system design. For example, Brabra et al. presented the behavioral aspect of Cloud Resource requirements based on state-machine models where entities or process delineated as state and their subsequent transaction are based on triggered conditions (Brabra et al. 2018). The strength of modeling has been observing recently in medical and health related CPS applications (Jiang et al. 2012; Guo et al. 2016). Jiang et al. presented a model for implantable pacemaker as their case study for modeling and verification of control algorithms for medical devices (Jiang et al. 2012). A patient and device model are created for a clinical scenario to validate and test the medical devices by Silva et al. (Silva et al. 2014). Similarly, Parveen et al. presented a component based hierarchical model of an ECG monitoring device – Holter Monitor, where each component of the hardware and computational part, is represented as an actor (Parveen et al. 2018). These studies indicate that by adopting the model-based approach to design such applications helps to detect and fix the problems at early design phase which gives benefits in term of making changes at model level and supports customization for individual scenarios (Lee et al. 2012; Lee 2015); this is an essential feature to design the health related applications. However, while a broad range of modelling tools and techniques have been presented, a little is known about CPS modeling and tools that can incorporate the physical dynamics with computation and communication.

To address this concern, we use an open-source software framework- Ptolemy-II. Ptolemy-II is based on an actor-oriented design where individual components are modelled as actors and interconnected to make a hierarchical model (Ptolemy-II 2019). Since the timing requirements are very critical in health related applications, especially for incorporating continuous monitoring requirements, verifying the behaviors of the system become essential. We used the UPPAAL model checker which uses state and transition based control structure with real-valued clocks, communicating through channels or shared variables (UPPAAL 2019).

2. Monitoring using wheelchair

In recent years, many wheelchair-based monitoring solutions have been proposed and presented which uses sensors, WiFi, cameras, Virtual Reality (VR) based devices, Oculus Rift, Head mounting displays, High Definition cameras and computer screens (Hashizume et al. 2018; Wästlund et al. 2010; Sato et al. 2014). These existing approaches are not suitable for our requirements in three ways: First, some of these existing approaches required a significant amount of control from the caregiver. Second, the systems are equipped with multiple assistive devices to control and monitor the wheelchair. Third, most of these assistive devices are expensive as well as create an additional burden for the wheelchair user to carry.

The researchers and practitioners advocate the needs for building a suitable solution for people having a various sensorial, motor and cognitive disorders, support elder care, or to serve individual's needs while incorporating the appropriate features (Carrington et al. 2014). The survey presented the necessity of having power assistive devices for better accessibility and interactive technology for the users, including wearable, chairable and mobile technologies (Carrington et al. 2018; Holloway et al. 2017). Considering the need for such self-monitoring system the proposed model design is encouraged by two following challenges:

A. Social Challenge. There is a social need for building low cost, modular, customizable wheelchair system for two reasons- 1. Easy of accessibility: affording expensive wheelchair monitoring system cannot serve the need of disabled people in developing countries 2. Use of familiar Technology: People, who have less exposure to the usage of these highly technical devices, face a challenge to operate these devices. To address these concerns our proposed design uses existing learned technology and familiar interfaces such as smartphone based input-output to operate the wheelchair.

B. Technological Challenge. The significant challenges in the design and development of such applications involving health related scenarios are with respect to their physical designs and control algorithms. We address this issue using by modeling control algorithm to automatize various aspects of path formation with limited computation requirement. For a hardware implementation, our design proposes COTS devices such as sensors to detect position and orientation, Arduino or Raspberry Pi3 as a microcontroller. The devices are installed below the wheelchair seat itself, which increase the comfort level of the user while moving (Carrington et al. 2014). These COTS devices have been used successfully in physical implementation due to their ease of availability, cost-effectiveness customizability, and modularity (Criado et al. 2018; Parveen et al. 2018).

3. Assistive navigation for indoor environment

Different navigation and positioning techniques have discussed in earlier research that includes infrared, Bluetooth beacons, RFID, UWB and Wi-Fi, Accelerometer, Gyroscope, and ultrasonic sensors for indoor space (Sakpere et al. 2017; Wattanavarangkul et al. 2013; Jensen et al. 2009). In the physical implementation, we plan to use the combination of Accelerometer and Gyroscope sensors to detect the current position and orientation of the wheelchair, similar to (Hsu et al. 2014; Marotto et al. 2013); and Passive Infrared (PIR) sensors for obstacle detection. Indoor navigation poses a challenge since GPS is not available to get the indoor house map and every house has a different map. Hence, in practical, it is difficult to load these maps in the application, we are solving this problem by creating a grid-based map of the house and storing it for further automatic navigation. Details explanation of the map creation is given in the following section.

System Overview

The layered architecture of AutoWheel System is illustrated in Figure.1 from the cyber-physical systems perspective. The physical layer represents the hardware aspect of the system. The computational layer depicts the components which are involved in computations such as path creation algorithm, processing of input-output from sensors and process executions as states transitions. The communication layer manifests the components which interact with the external systems such as cloud via the internet and a mobile app which gives a signal to move the wheelchair. The mobile app which is controlling the wheelchair communicates through the controller. The layers and the components inside them are categorized based on the logical flow of the system rather than physical. Though the components of the computational layer physically reside into the Raspberry Pi3 controller, to make the system modular from the development perspective, we treat them as a separate layer. The microSD card is attached to Raspberry Pi3 stores the data of various states of wheelchair movement, timestamp and alarm notification. This data can be sent to the cloud or internet via mobile for further analysis and monitoring; this included in our future work. Section "System Model" explains how AutoWheel system works.

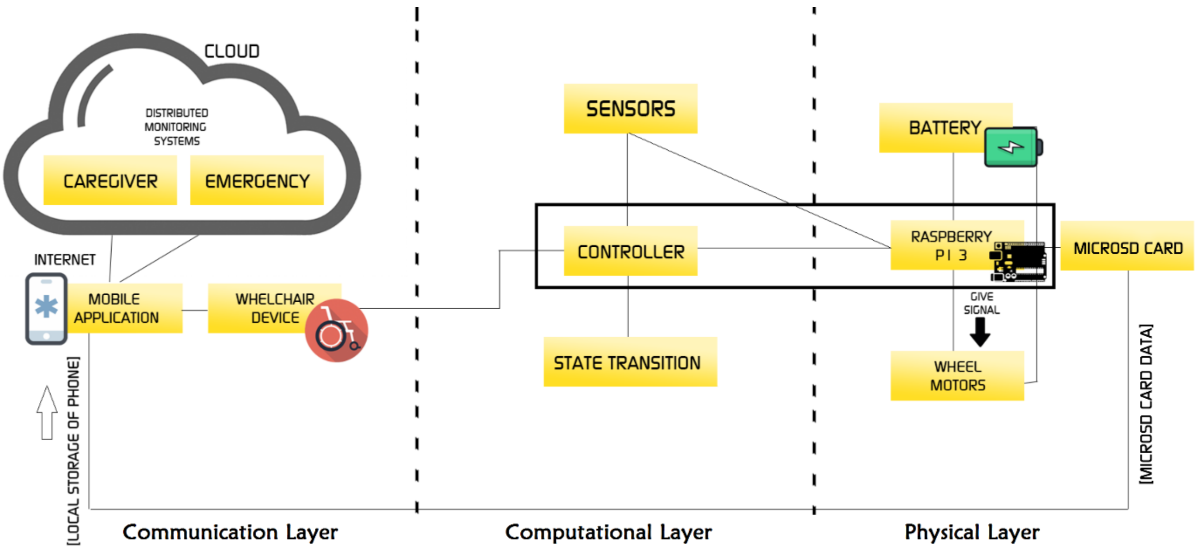

Figure 1. Architectural overview of the system

Figure. 2 represents how each component is logically implemented as a class or package using the Eclipse Java framework. Figure. 2 shows a class diagram of our source code. This class diagram is generated via ObjectAid extension which is integrated into Eclipse (ObjectAid 2018). Each class inside a package is designed cohesively to address the reusability concern. For example, the IO package represents the classes which are intended for taking or sending different types of inputs-outputs based on the actual input-output devices used in the system. Subsection 3 of "System Model" section further provides an explanation of these components behavior while executing processes, by one example scenarios.

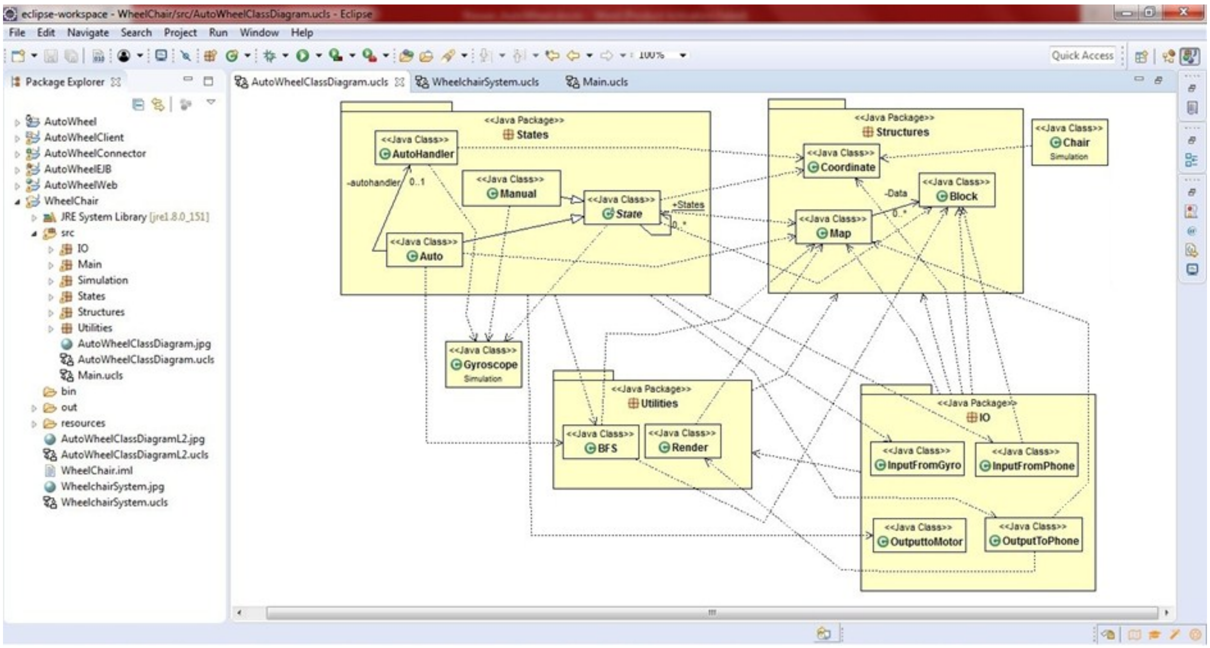

Figure 2. Class diagram generated from the source code in Eclipse

System Model

In the proposed design, the system allows the user: wheelchair person or Companion, to set the destination position via the mobile app. An environmental map of the house is created during the installation phase which is a manual process. The wheelchair first move around the house, store each step and construct the path, marking all the static obstacles. When next time the user wants to ride, she needs to click on the map where she wants to go– destination coordinates are rendered, the wheelchair will automatically follow the saved safe path from the current location coordinates and place itself in the given coordinates. The system keeps recording coordinates as the safe path each time wheelchair moves. This way, the entire house is converted into a grid-based map, see Figure. 3 *d*, each square block is constructed by taking x-y coordinates and margins of the wheelchair so that it restrains itself from colliding the nearby walls or objects while moving, and marked each block as safe or unsafe (see block class under structure package in Figure. 2).

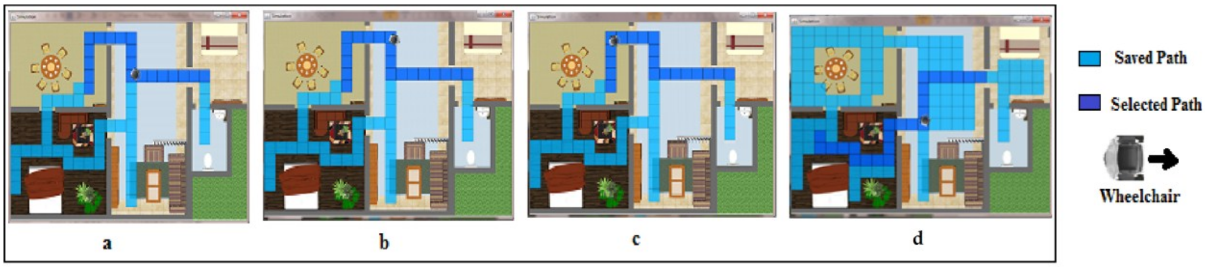

Figure 3. The 2D floor plan shows the saved and selected path for navigation (*a*, *b* and *c*). Image *d* depicts how the entire house converted into a grid-based map and wheelchair following the safe path

Figure. 3 shows a 2D floor map which is representing a scenario where door-to-door paths are created. Figure. 3 *a*. shows wheelchair is moving on a selected path, taking the first turn. Figure. 3 *b*. and *c* shows the wheelchair taking second turn and third turn respectively. Figure. 3 *d*. shows the grid-based map of the entire house. The complete scenario of taking turns while ensuring the safety is modelled in Ptolemy-II, explained in the next section. Furthermore, we included two scenarios in our path constructing algorithm:

Alarm Raising Scenarios: the alarm condition are triggered in three cases 1. If wheelchair stops abruptly and does not move for more than the threshold time, considering the user has not pressed the Stop button; 2. If wheelchair's speed is exceeding the threshold limit of the accelerometer signal; 3. If the user presses the emergency button.

Emergency Notification Mechanism: In case of an emergency signal detected through Alarm or via emergency button press, it notifies the caregiver via a mobile app.

1. Modeling Safe Traversal using Ptolemy-II

In wheelchair mobility, taking safe turns is very important for the user. This section explains how the safety during the turns are modelled in Ptolemy-II (Ptolemy-II 2019). In our Ptolemy-II simulation, we inserted coordinates of source and destination to make various trajectories in the path creation into the model. Figure. 4 exhibits system component view for automatic path creations in AutoWheel. Given the wheelchair's current position and destination coordinates, it forms the trajectory. To ensure the system works correctly in case of multiple turns or obstacle lies on the path, we have done the simulation using two turns, depicted in Figure. 5. While making these trajectories, safety margins are incorporated for wheelchair's length and width; this ensures the automatic path makes enough space for the wheelchair to move around without touching or colliding with nearby objects, corners or house walls. In case if the wheelchair is reaching close to any obstacle or deviates from the created path, the system generates an alarm signal and stops the wheelchair.

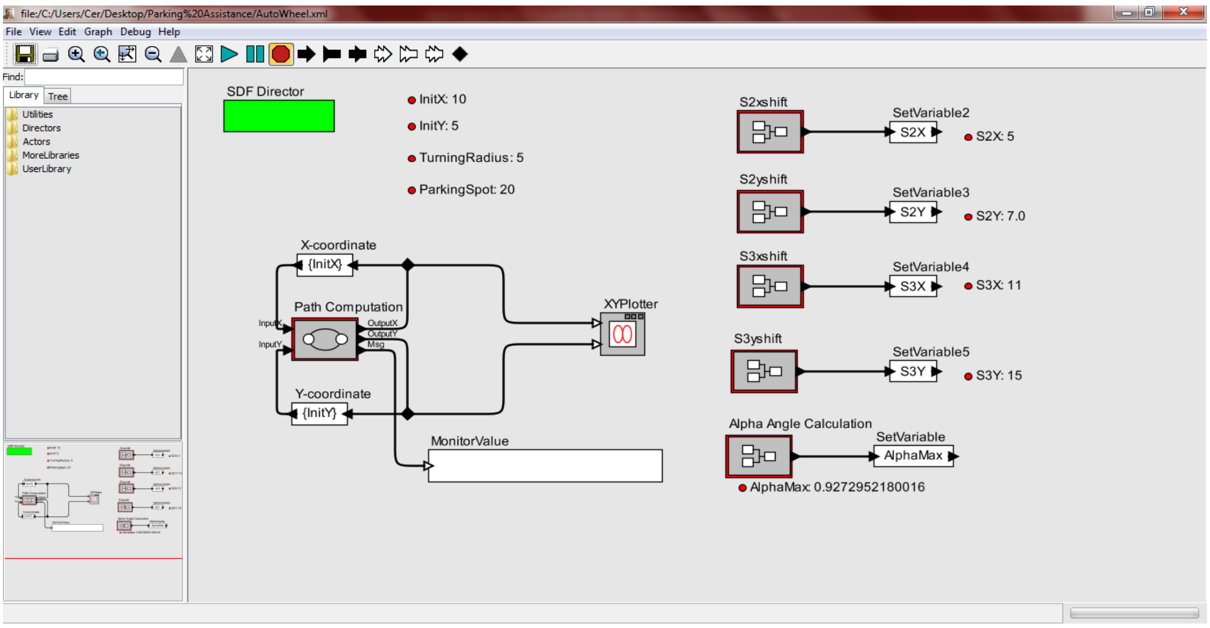

Figure 4. Actor-based model of the system

Path calculation for safe turning experience

This section explains the process of trajectories creation. We have taken a scenario where the user has to move from (X1, Y1) to (X4, Y4) considering a straight path is not possible due to the obstacle presents on the way. The system initializes by creating margins of wheelchair body considering its width and length.

The entire path calculation is divided into four states as presented in Figure. 7.

S1: (X0, Y0) → (X1, Y1)

S2: (X1, Y1) → (X2, Y2)

S3: (X2, Y2) → (X3, Y3)

S4: (X3, Y3) → (X4, Y4)

User's initial position coordinates are set as (X0, Y0) and destination coordinate set as (X4, Y4). For a straight path, **α** calculation does not require (**α** is angle responsible for creating turns). In the case of turns, curve perimeter needs to be calculated. The path depicted in Figure. 5 shows the first turn from (X1, Y1) to (X2, Y2), the second turn from (X2, Y2) to (X3, Y3). We called this perimeter as *AlphaMax* which represents the maximum value of **α** angle. The coordinate X3 is equal to $(X0 - R + 2*R*\cos(\alpha))$. The distance (X3 - X0) can be obtained from the sensors and graph. For simulation purpose, we set this distance and turning radius *R* with fixed parameter values. Additionally, *AlphaMax* is calculated based on the restraints set by the distance between the initial and final coordinates. In this model, **α** angle calculation done by assuming that these coordinates lie along the same line. While others, such as (X2, Y2) are calculated using various trigonometric relations between the coordinates.

The distance between the coordinate set is calculated through various composite actors of Ptolemy-II. The values generated are stored in shared parameters and are accessed as guard conditions for state transitions as presented in Figure. 7. All state transitions are handled by comparing the set of coordinates generated from the currently executing state to the set of parameters calculated during the initialization process. These states show how the system's process goes through various states and transitions during path creation. Each guard condition is mentioned explicitly in the Ptolemy-II *ModalModel* actor.

2. System behavior analysis using State Machine Model

The path formation states are exhibited in Figure. 7 represent a mathematical relationship between the input and the output, which essentially describe the path followed by the wheelchair. We picked up a scenario where the wheelchair has to take two turns to reach the destination. Automatic movements consist of the following states:

STATE 1. The initial location, a destination spot and a predetermined turning radius *R* of the wheelchair, are given. Radius *R* is a measure of how sharply the wheelchair can turn. This state executes a linear increase in Y, without changing X, until the wheelchair approaches the appropriate point to start turning. The number of executions of this state varies over a wide range, an extreme case being when the wheelchair starts turning very close to the initial coordinates.

STATE 2. This state serves the purpose of an 'intermediate' state from state 1 to state 2, depicting the one-fourth of the anticlockwise turn then moves to STATE 3. Turn wheelchair left to the maximum possible turning angle, which makes the center of the rear wheel moves along a circle of radius equal to the wheelchair's turning radius. It continues on this path till the wheels turn through *AlphaMax* radius. The wheelchair rotates through the required angle along a circle until it is aligned along the tangent common to the second circle, which is considered as a required motion of the wheelchair in case of multiple turns in the given scenario.

STATE 3. This state shows the wheelchair movement of turning into the specific spot via forming a clockwise half-circle. The entirety of this state traces an arc of a circle, which shares a common tangent with the circle described in the second state. For clockwise direction, it will turn the wheel to the extreme on the right side, making the wheelchair turn along a geometrically identical circle, but in the opposite direction. The state continues till the maximum y-coordinate is reached on the path; this would be in-line with the destination spot, and along the tangent parallel to the x-axis.

STATE 4. The wheelchair continues to move along the tangent at the end point of the previous state and eases into the destination spot.

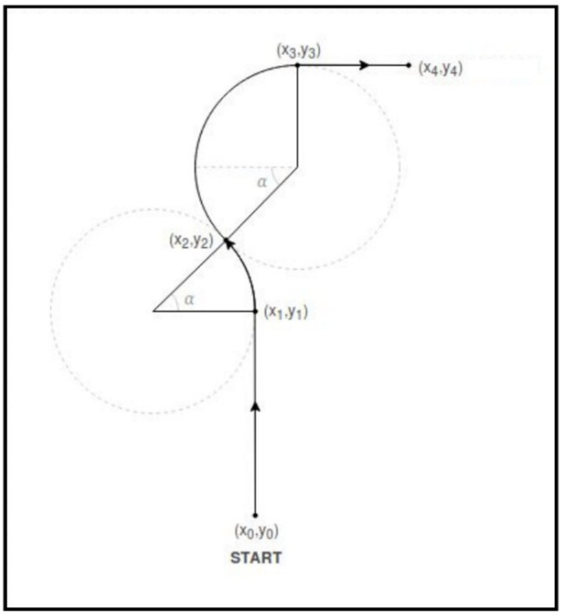

Figure 5. A Scenario of taking two turns

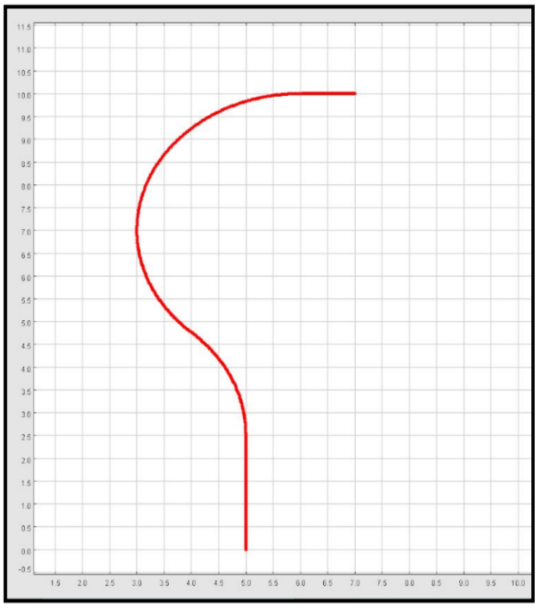

Figure 6. Simulation Result: the XY potter shows the trajectory created

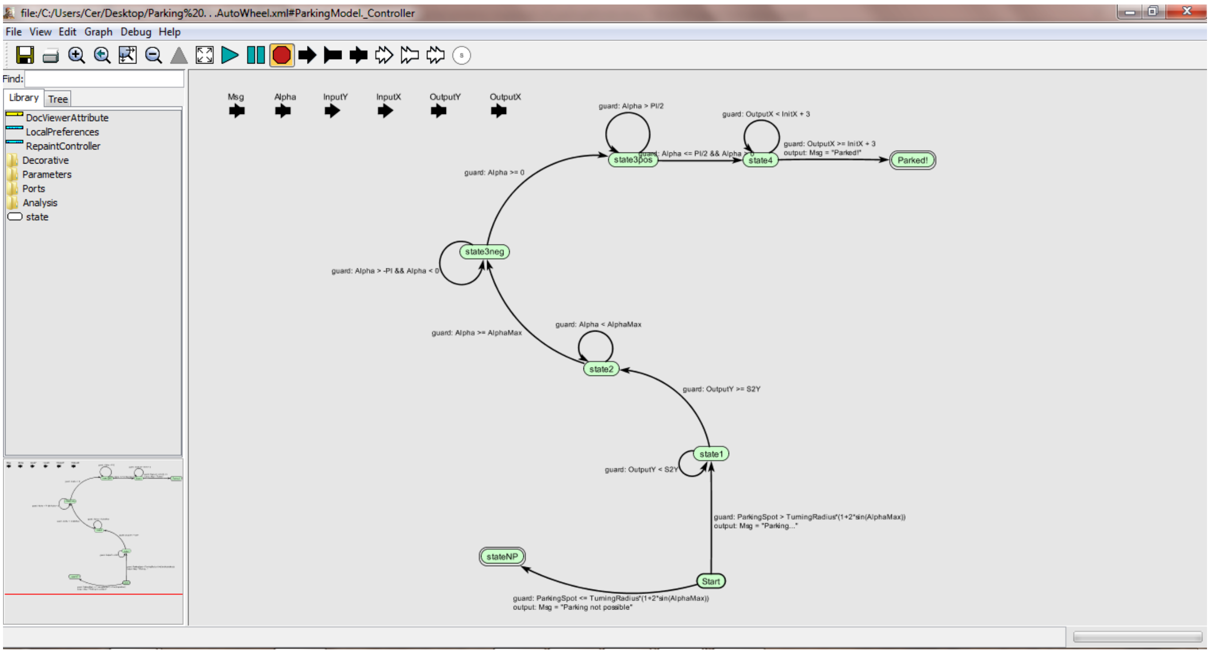

Figure 7. The states represent the movement of the wheelchair during turns. It shows how the system's state transitions take places based on various guard conditions for implementing safe turns

STATE 2 and STATE 3 Refinement.

State 2 and State 3 are executed as follows:

- Shift input set of coordinates towards the origin, such as the center of the circle along which the wheelchair turns lies on the origin.
- Convert the coordinate system from Cartesian to Polar, allowing for the appropriate motion to be achieved by changing just one parameter (the angle, while the magnitude remains constant) and not two (both X and Y).

- Increment the angle by a small amount to achieve the smooth motion. The logic is the same as applying differentials.
- Convert the coordinate system back to Cartesian, and shift the graph back to the original position, and output the values as X and Y.

The Ptolemy-II execution of STATE 2 is illustrated in Figure 8.

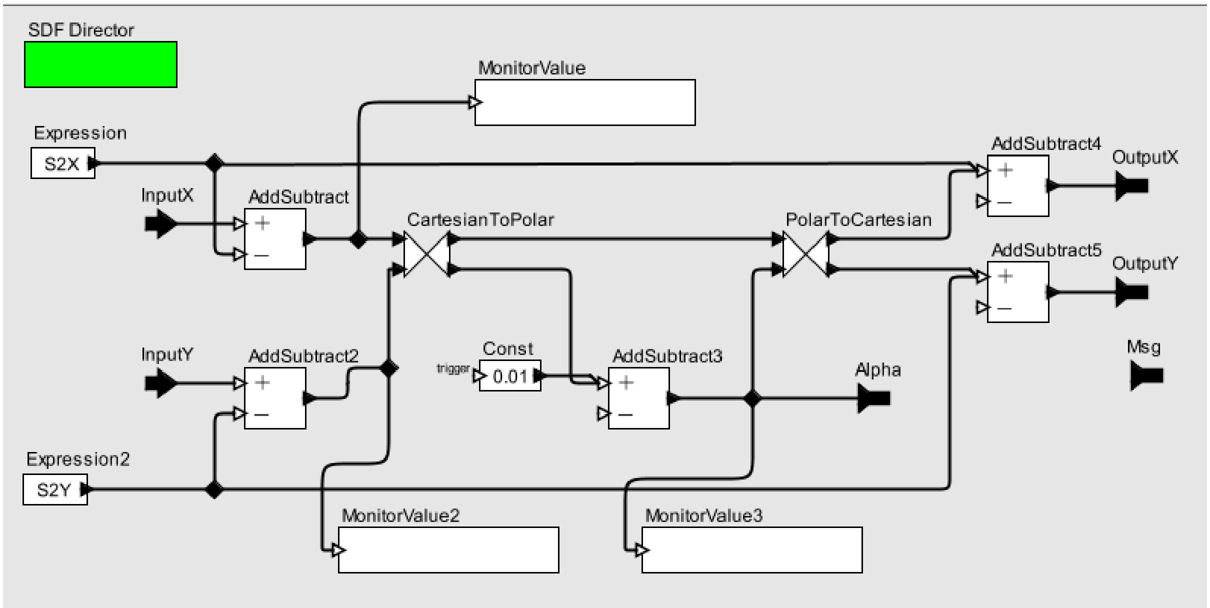

Figure 8. Refined Model of State 2 and State 3

The modelling of STATE 3 is divided into two parts, one for positive turning radius, and the other for negative, implemented the same way as STATE 2 is implemented as described above.

Simulation Result. The initializations and subsequently generated parameters created the output as shown in Figure 6.

3. *Verification of the system behaviors using UPPAAL*

To verify the AutoWheel's correct behaviors, we used the UPPAAL tool. Each component of the system further abstracted in term of its internal states and behaviors with respect to the other component running in the system. The processes for each component are depicted in Figure. 9. We present one example scenario briefly as following to show how each process is synchronized with the other process to perform a dedicated task.

Example Scenario. Algorithm component starts measuring the position of the wheelchair as per coordinates received from sensor (i.e., Gyroscope). For example, when *Algorithm* receives a signal to move *front*, it passes this signal to *MotorController* module. *MotorController* sends *MCtoM_F* (*MotorController* to *Motor_Front*) signal to *Motor*. *Motor* triggers *MtoW_F* (*Motor* to *Wheel_Front*). *Wheels* start moving forward. *Gyroscope* sensor measures the positions and triggers *update* signal to *MapUpdate*. Simultaneously, the algorithm will be recording the path as per the *MapUpdate*. One of the safety scenarios here is – wheels are in the idle state until the correct signal is received from the *Motor* and *MotorController*. In order to process the correct transition further, *MotorController* must receive the signal from the *Algorithm* where algorithm continues measures the position and direction by taking data from the sensors. Transitions between the two states are triggered when it satisfies the given guard conditions and fulfills the requirement of the target state. Hence, the correctness of the process in the system is ensured when multiple modules are reciprocally connected in CPS environment. This scenario is depicted as a *Message Sequence Chart (MSC)* in Figure. 10. MSC view in UPPAAL shows the synchronizations between the different processes and their current states. The scenario mentioned above is to demonstrate the initial insight on how components interact based on the given constraints. The detail explanations of the verification scenarios are not included in this paper.

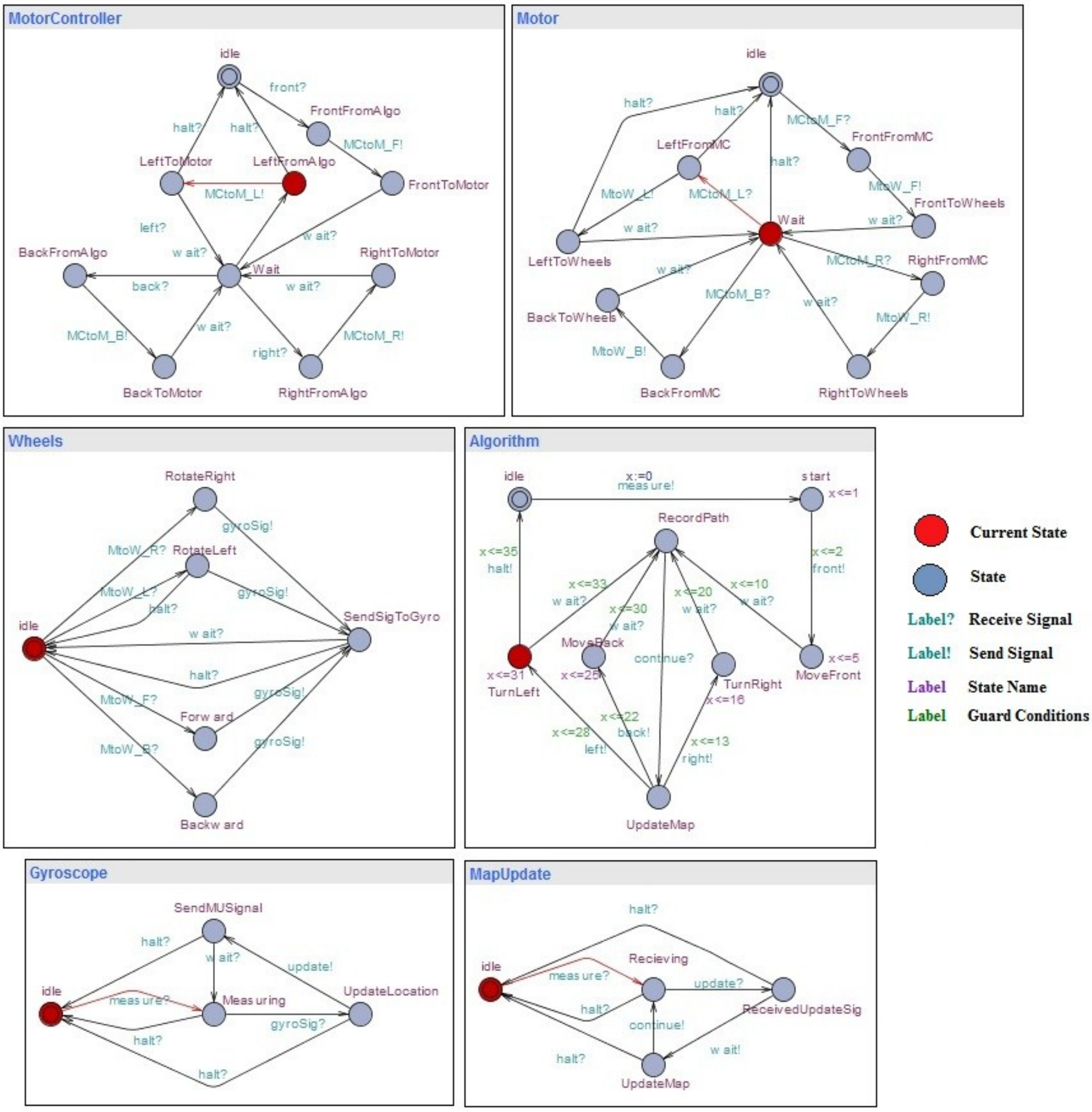

Figure 9. Components of the system go through various states during process execution with respect to the other components based on synchronized signals

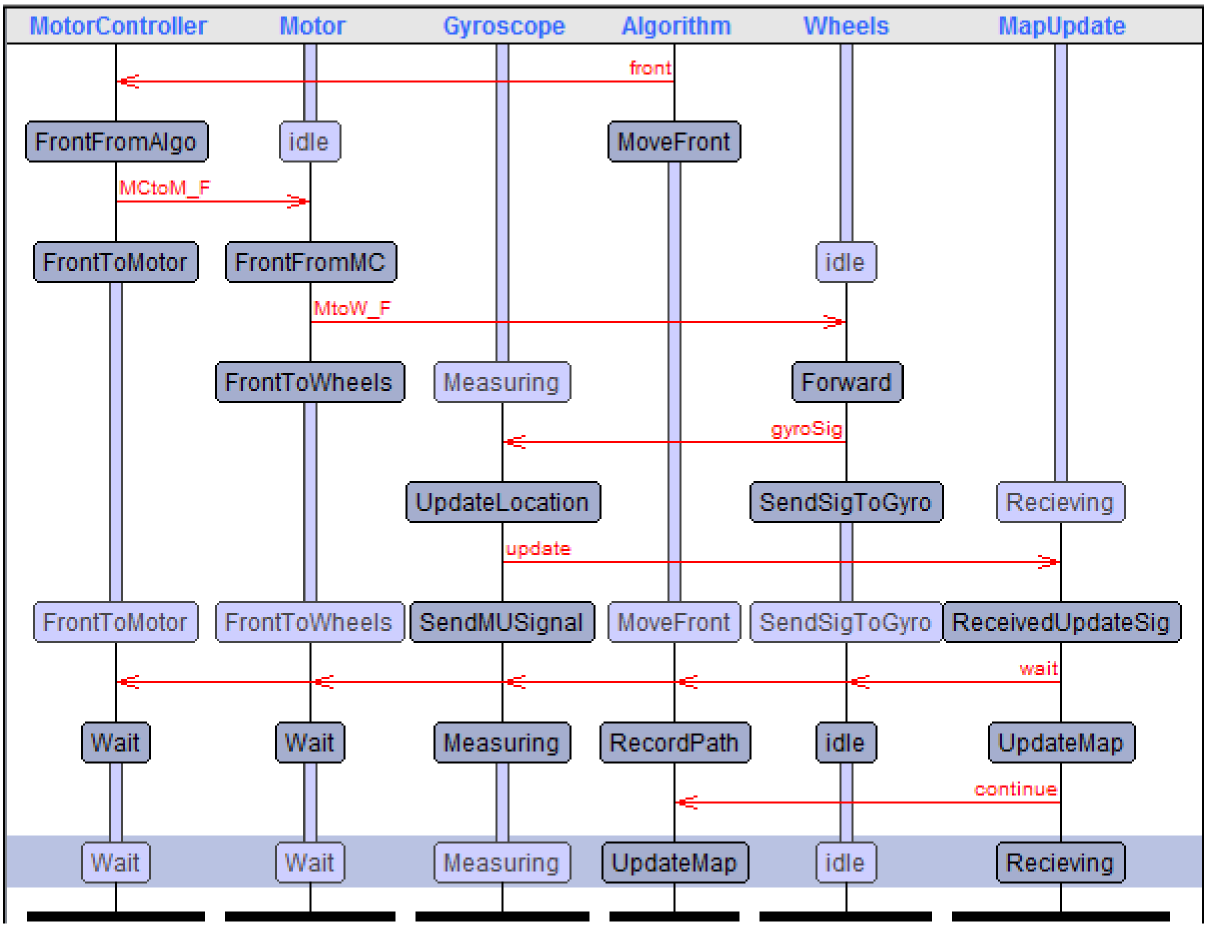

Figure 10. A Message Sequence Chart depicts the executions of the state's transfer based on triggered conditions and signals

Prototype Implementation

COTS Components provide various benefits in term of affordability, modularity, and flexibility in the implementation of the system. The hardware implementation has been prototyped using a robotic car as shown in Figure. 11. Our plan includes the hardware components for the implementation as given in Table 1.

Device	**Cost (US Dollars)**
Raspberry Pi3 with 16 GB MicroSD card	61.36$
HC-SR04 Ultrasonic Sensors/Gyroscope and other sensors	2.79$
Two DC Motors	55.78$
Amron Lead Acid Battery	44.62$
Miscellaneous items	5$
Total	***169.55$***

Table 1. Approximate Cost calculation of AutoWheel System

We estimated that the total cost of AutoWheel system is 169.55$. This cost is much lesser than the existing automatic wheelchair available in India.

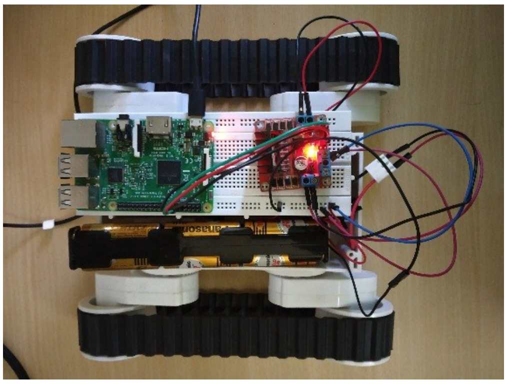

Figure 11. Hardware prototype of AutoWheel system

Our Findings and Limitations

In this paper, we have modelled a controlled algorithm, which creates trajectories by calculating the path and convert the house into grid based map. We modelled the safety requirements of the wheelchair using Ptolemy-II and briefly present the insights of modeling system behavior using UPPAAL tool. We used the state machine model to elicit the behaviors of the individual process running within each component while considering their synchronized behavior over time. From this experiment with modeling tools, we observed that modularity can be achieved in design as Ptolemy-II provide an environment where each participating component can be modelled cohesively as an actor at granular level of design, at the same time, these actors are interconnected to perform a dedicated task and can be visualized as higher level design.

Furthermore, our findings are categorized as the following:

1. Design of the artefact – the effectiveness of the model can be improved by placing human users in the number of use-cases and modeling individual scenarios for specific needs.
2. Significance to research and practice – we find that Model-based approach can be successfully used for health related CPS applications developments for two reasons 1. It helps to address the architectural attribute Safety, usability and most importantly modularity both at software and hardware level. 2. Easy plug-and-play architecture as the control algorithm is independent of the hardware used in the design which gives an apparent abstraction and separation of concerns from a design perspective, concerning the separation of information, communication and physical part of CPS as depicted in Communication, Computational and physical layers of our design, Figure 1. Although there are various COTS based applications are present, our study shows the usefulness of COTS components in the initial testing phase of CPS development (i.e., prototype testing or algorithm testing) which is expensive otherwise.

However, the presented work has some limitations. The design presented in this paper is not handling scenarios such as moving upstairs downstairs direction, slope and slanting surface, pit detection, fall detection. Our case study provides only an initial insight for using model-based approaches for health related applications in CPS domain. Additionally, detailed investigations are required to model other non-functional aspects in health related CPS development such as reliability and security concerns.

Conclusion and Future Work

We proposed a model-based design for an automatic wheelchair system, called AutoWheel. The objective of AutoWheel project is to identify how the model-based approach and CPS tools can be used successfully to implement complex health related scenarios. The applicability of this approach is demonstrated as our artefact (Model and Prototype). We modelled one aspect of safety scenarios in the given context. Furthermore, various architectural scenarios can be modelled using this approach. The proposed design has a consideration on utilizing the wheelchair' workspace which increases the comfort level and helps users to move freely. We plan to incorporate the more non-functional scenarios in our Ptolemy-II based model. For example, we also intend to enhance our design by implanting the scenarios of controlling the wheelchair remotely using Cloud-based technologies, in which caregiver can controller the wheelchair remotely. From the future research perspective, we observed that research needs to be evolved in order to enable health industry to exploit the full potential of CPS, especially when it is required to identify what model, methods or tools should be used to implement, experiment or perform validation of the design.

Acknowledgements

We gratefully acknowledge the help from our friends A. Baskar, Rahul Parashar, and Pruthvi Duvva, in helping shape this work.

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