Development of Modular Framework for the Semi-Autonomous RISE Wheelchair with Multiple User Interfaces Using Robot Operating System (ROS)

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***Abstract*— Electric wheelchairs are widely used by individuals with various forms of physical disabilities. Typically, these wheelchairs are controlled using a steering device (e.g., joysticks). However, for people with limited physical mobility, the incorporation of semi-autonomous navigation and control within electric wheelchairs can considerably improve their mobility and quality of life. In this paper, we present the development of a re-configurable framework and user interfaces for RISE wheelchair, which provide flexibility and customizability depending on the nature of the disability of the users. At the same time, effective navigation and obstacle avoidance capabilities are incorporated using Simultaneous Localization and Mapping (SLAM) that allow the RISE wheelchair to navigate in different environments. A goal estimation algorithm has also developed in order to travel from the current location to the destination with minimal guidance from the user. In this paper, the various aspects of the RISE wheelchair will be discussed, ranging from architectural development, simulation, and practical experimentation to evaluation of the functionality and feasibility of the various modules.**

***Index Terms*—Simultaneous Localization and Mapping (SLAM), Visual Odometry, Robot Operating System (ROS), electric wheelchair, rehabilitative robotics**

I. INTRODUCTION

In the United States alone, the people suffering from various disabilities amounted to 12.5% of the total population in 2015 [1]. The different types of disabilities include physical, hearing, vision, ambulatory, self-care, independent-living, and cognitive disabilities [1], where each form of disability poses a host of different risks and challenges for the individuals and their families. The chances of leading a normal life for the disabled individuals are minimal, especially in regions of the world with higher levels of poverty, wage gaps, and lack of social inclusion within the society [2]. The use and practical application of various technological advancements has allowed some level of mobility to the physically disabled individuals. One example of such applications in the RISE wheelchair, which is given in Fig. 1. However, the entailing high costs and limited availability of such amenities prevent their widespread usage in various societies [2].

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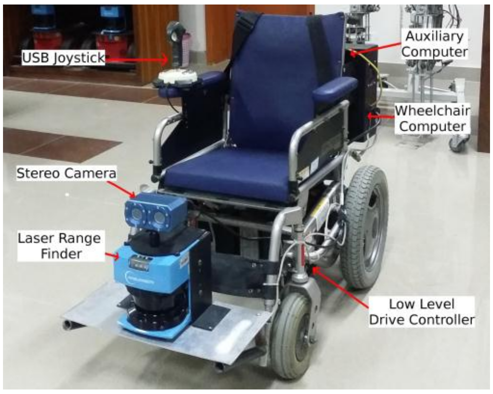

Figure 1. RISE Wheelchair Platform

Recent advancements in the field of mobile robotics have shown promising results for developing technology that can notably improve the lives of physically disabled individuals. Intelligent wheelchair-based research projects remain an active research area, which is being actively investigated by different research groups around the world [3]–[6]. In this regard, researchers at one of those groups have developed a modular and semi-autonomous Smart Wheelchair Component System incorporating sonar and infrared sensors [4]. Similarly, another wheelchair discussed in [5] utilized camera and inertial measurement-based sensors based on the principles of dead reckoning that allowed manual navigation based on saved paths within known environments. The Intelligent Wheelchair [6] detected landmarks using visual information and navigated autonomously using sonar, infrared and vision-based sensors sonar-, infrared-, and vision-based sensors. In the Intelligent Wheelchair System developed in [7], a combination of gesture and facial expression recognition was used to take input from the users, and a combination of vision and sonar sensors was used to navigate from the initial position to the designated location. Wheelchair developed by INRO [8] allowed autonomous navigation as well as wheelchair convoy formation and management using Sonar and Global Positioning System (GPS). Similarly, Luoson III [9] used sonar, vision, and inertial measurement-based sensors to assist in navigation, along with the ability to follow and track moving targets. SIRIUS [10] is another wheelchair project that can save routes and follow the recorded routes at the users' discretion. It can also avoid obstacles by using sonar sensors.

Within this research, an effort has been made to ensure that a number of different features not previously addressed in the literature could be incorporated in the RISE wheelchair. Some of these features include the use of multiple user interfaces to allow better usability for individuals suffering from varying forms of physical disabilities (ranging from limbic muscular deformities and partial paralysis to motor neuron disease and paraplegia) as well as plug-and-play configuration-based architecture using the Robot Operating System (ROS) to allow seamless addition and incorporation of features and different hardware platforms to provide a reliable performance. In this research, an assistive robotic wheelchair system has been developed that attempts to incorporate the needs and specifications of the user community in mind for providing a mobility solution to individuals suffering from varying levels of physical disabilities. In section II, an overview on the different aspects of the system architecture of the RISE wheelchair will be provided. Section III will expound on the results of the simulation and practical experimentation conducted on the RISE wheelchair. Future improvements on the RISE wheelchair will be highlighted in section IV.

II. System Architecture and Design

This section will discuss the different components of the system hardware and software architecture, which enable the RISE wheelchair to perform a list of different functions that includes functionality for supporting multiple-user interface-based wheelchair control, object detection and avoidance, simultaneous localization and mapping, and proposed algorithm for effective semi-autonomous navigation. The modular, plug-and-play nature of the hardware architecture stems from the need for incorporating the various specifications and catering to the different physical limitations of the disabled individuals. For example, individuals suffering from the loss or impairment of the proper functioning of the lower limbs might be able to navigate the wheelchair using a joystick-based control. However, a similar control configuration might not be suitable for individuals suffering from upper- or full-body paralysis. Therefore, the plug-and-play configuration of the system's architecture allow modifications in the wheelchair controls. At the same time, the modular nature of the system's architecture facilitates the easy upgradation of the hardware modules in response to changes in the technological enhancements and the users' needs in the future. The complete details of the RISE wheelchair system have been outlined in Fig. 2.

It can be seen from Fig. 2 that the architecture of the RISE wheelchair can be divided into the following four parts: (i) steering devices (e.g., eye camera for control using eye-gaze gestures, EEG headset for using brain-controlled interface, tablet for touch-based control and joystick for manual control); (ii) collation of sensors for safe driving and navigation (e.g., laser-range finders, stereo-vision camera, battery, and motor drive); and (iii) on-board computational resources for using sensor data to perform localization, mapping, and obstacle avoidance. The current RISE wheelchair framework has also the capability to incorporate a robotic manipulator for aiding the disabled individuals (especially those unable to move their arms) to pick up/place and use different objects. In Fig. 2, a HMI *Tablet* has been used as the intermediary module for connecting various user input devices (e.g., eye camera, joystick, EEG headset) to the *Vision PC* (a secondary computer device used for handling the data from the different user input devices) and the *Cobra PC* (a primary computer device, which combines the user commands with feedback from different sensors for environmental perception and navigation to safely reach from the initial to the final position, as specified by the user). In order to incorporate multiple-user interfaces, the existing communication protocol between joystick and motor control was decoded to facilitate the development of multiple user interfaces.

The developed framework for the RISE wheelchair provides a hierarchical approach, which specifies that the low-level functions and decisions, such as collision avoidance, are performed by nodes directly connected to the sensors (e.g., motor control and laser-range finder), whereas higher order decision-making is controlled by nodes that define the overall behavior of the mobile platform. ROS was utilized for the development of a standard robotic platform architecture for the RISE wheelchair, which considerably facilitates the integration of additional components to the existing robotic framework. Due to the easy portability and transferability of the defined ROS-based framework from one platform to another, the robustness of the proposed framework can be easily assessed on different mobile platforms.

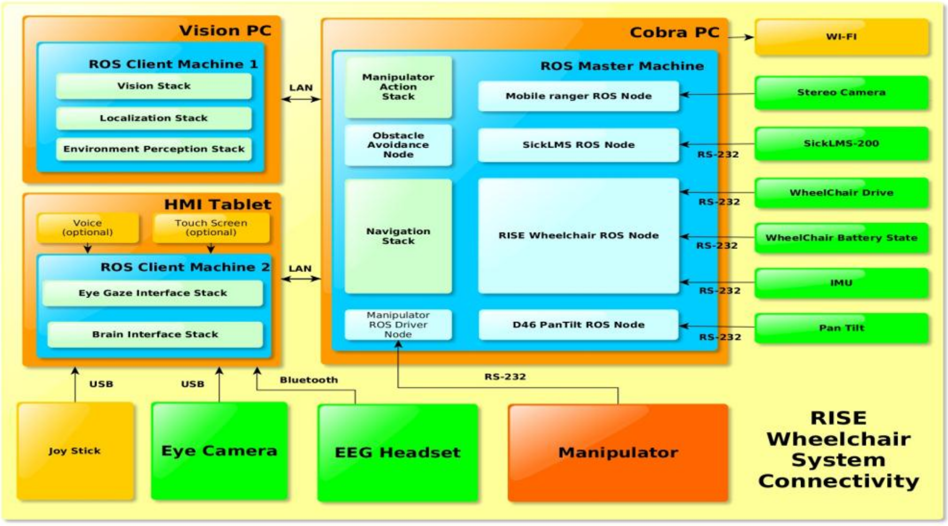

Figure 2. Architectural overview for RISE wheelchair

III. Experimental Results

This section will discuss the results of the experimental testing of the proposed architecture for a rehabilitative mobile platform, namely the RISE wheelchair. In order to elaborate on the different phases of the actual testing, this section will be divided into four sub-sections, which will discuss the different modes for development and feasibility assessment of the semi-autonomous RISE wheelchair. In the first sub-section, the results pertaining to the 3D modelling aspect of the RISE wheelchair on *SolidWorks®* will be discussed, along with the environmental simulation results on ROS for map generation using sensory feedback. In the second sub-section, the results of the testing for the RISE wheelchair will be highlighted in response to the different user interfaces proposed for the users afflicted with varying level of physical disabilities. In the third sub-section, the results of the practical experimentation for localization, mapping, and navigation of the RISE wheelchair will be highlighted, along with the different algorithms utilized for analyzing the sensor data. In the fourth sub-section, the proposed goal selection algorithm will be discussed, which is designed to allow disabled individuals to navigate manually from one point to another, while relying on minimal user input.

A. Simulation

In order to facilitate the accurate simulation of the RISE wheelchair, its 3D model was developed, which contained all of the necessary parts with exact dimensional specifications. Fig. 3 outlines the 3D model of the wheelchair. This model was incorporated within the ROS-based simulation during the map generation, localization, and development of the interface for goal generation, which will be discussed in the proceeding sections of the paper. Apart from the 3D model, the simulation of the actual environment for localization and mapping played an important part. The result of the environment simulation is given in Fig. 4. The map generation relied on the sensor data from the laser-range finder, which aided in the development of a simulated model for the actual environment. The simulated map of the actual environment was updated based on the availability of the sensor data pertaining to specific locations within the environment.

B. User Interface

The multiple interfaces for the control of the RISE wheelchair have been developed in view of the diverging needs of the different users in mind, which are essential for developing technological solutions that cater to different types of disabilities of disabled individuals. Consequently, the different needs and specifications of the users pertaining to their different physical disabilities can be easily included without the need for radical changes in the system's hardware, architecture, or physical design of the RISE wheelchair. Some of the different forms of user interfaces provided include: (i) joystick or smart phone-based control (people with partial or full functionality in one or both hands and/or arms can easily use the joysticks and touch screens for moving and navigating the wheelchair directly), (ii) eye movement-based control (a head-mounted camera focusing on the gaze-based gestures and eye movement of the users), and (iii) EEG-based control (brainwaves from an EEG headset are used to generate commands to control the wheelchair, as shown in Fig. 5).

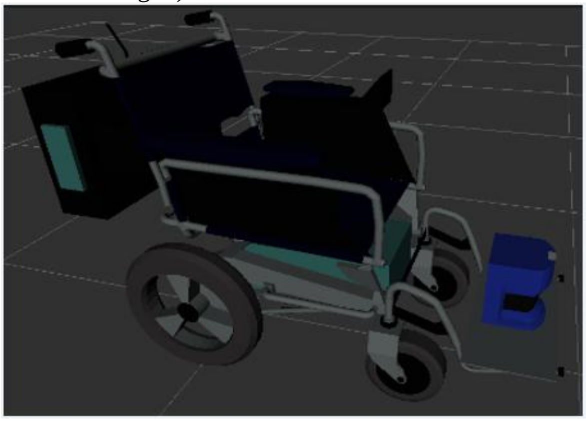

Figure 3. 3D model of the RISE wheelchair.

Fig. 5 demonstrates the practical working of the RISE wheelchair with the help of the EEG headset, which requires training of the users prior to initiating the brain commands for movement and navigation of the wheelchair in different directions. The different choices of the user interfaces for driving the wheelchair were based on survey and regular interactions with the wheelchair users' community, who were able to highlight the different hurdles and difficulties faced in the day-to-day life and the different ways in which improvements could be proposed to enhance the functionality and usability of the RISE wheelchair. Fig. 6 shows the usage of an eye-camera to facilitate the control and navigation of the RISE wheelchair, along with the output of the users' gaze to direct the movement and direction of the wheelchair. The level of physical disability was the primary factor, which ultimately dictated the type of control interface suitable for any particular user. For users with fully or partially functional upper limbs, joystick and smart phone-based controls were deemed to be suitable options, whereas for users suffering from physical impairments (resulting from accidents, injuries or birth defects) as well as ailments (such as motor neuron diseases and various other neural and/or muscular degenerative diseases), it is more suitable to use an eye gaze-based user interface and control system. When comparing the eye gaze-based user interface with the EEG-based user interface, field experiments and surveys of different wheelchair users provided the insight that the majority of the users generally preferred the former to the latter, as EEG-based user interface required prior training and long-term usage was not possible due to the limited battery timing of the *Emotiv*® EEG headset.

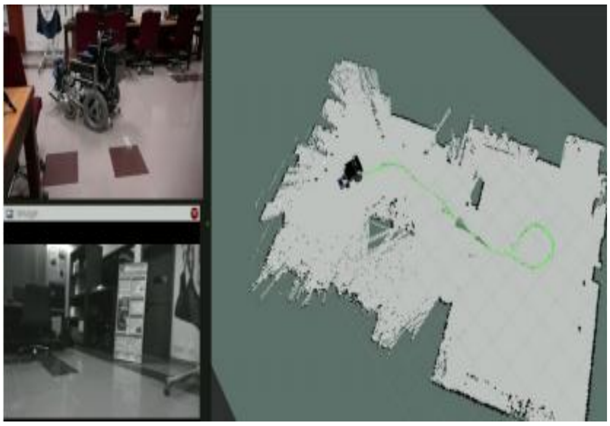

Figure 4. Results of environment simulation in ROS and camera feed .

C. Localization and Mapping

Localization and mapping are two of the most important high-level features of intelligent mobile robotic platforms. Localization allows the mobile robots to know their actual position within a given environment while the mapping of the environment is critical for awareness of its various features (e.g., location and dimensions of the different obstacles as well as dimensions of the room and level of accessibility of each location within the environment for the mobile robot). In order to accurately highlight the utilized localization strategy, Fig. 7 outlines the internal details and gives a brief overview of the proposed localization algorithm. The accurate implementation of localization and mapping is essential as it allows the extraction of robust features from the environment in order to avoid collisions, bumps, gaps, and other inaccessible areas in the environment, which can potentially cause discomfort or endanger the safety of the user in any way. It can be seen from the Fig. 7 that the first step in the localization requires pre-processing of the information received from each frame of the stereo vision camera.

Figure 5. One of the authors using an EEG *Emotiv*® headset to drive the RISE wheelchair.

In order to perform pre-processing, data from any given frame are extracted from the stereovision camera by corner extraction using FAST features [11] and computation of 512-bit string for Fast Retina Key Points (FREAK) descriptors [12]. The matching of key points between the left and right cameras for FREAK points is based on Hamming distance. The FREAK descriptors were used instead of SIFT as calculation of FREAK descriptors is 100 times more computationally efficient in comparison with SIFT [12]. The second step involves the calculation and prediction of the wheelchair's orientation in the near-future (for time $k + 1$), provided that the existing pose of the wheelchair is already known (for time k), which is calculated using Sigma Point Kalman Filter (SPKF) [13]. The stereo motion estimation is performed using features extracted by calculation of 3D and 2D points from two different time frames, namely k and $k + 1$, as given in Fig. 8. In order to update the change in the pose of the wheelchair, the feedback from sensors is used to periodically recalculate and update the values of SPKF.

Fig. 8 outlines the flowchart for calculating the visual odometry. It can be seen that data from consecutive frames are used for calculating neighborhood points for the frames at the times $k - 1$ and k. In the neighborhood search, the 2D points in the current frame k are matched with the 2D points in the previous frame $k - 1$. The 2D points in the frame $k - 1$ are calculated from the 3D points. After the 2D and 3D points are calculated and the motion estimation is performed, the SPKF algorithm is used for pose calculation and estimation while any variations in the values between two consecutive iterations are used for error minimization by comparing the predicted values with the actual calculated values for every frame of the stereovision camera.

D. Algorithm for Goal Selection

The purpose of this sub-section is to provide a goal selection algorithm, which can allow the user to specify the directions to control the RISE wheelchair with minimal physical movement. In this manner, the wheelchair can traverse from the current location to the desired destination with minimal user input requirements, ideal for individuals with severe physical disabilities. The simulation of the 3D environment reduces the number of dimensions by a single order. In order to find and select a location within the given 2D map of the environment, a line from the actual location of the mobile robot on the 2D map rotates in a clockwise fashion (similar to the hands of the clock) to allow the user to select any location by using a single push button. Fig. 9 provides the pseudocode with a detailed overview for the selection of a goal point within the known indoor environment.

IV. Conclusion and Future Works

In this paper, an architectural framework for a semi-autonomous wheelchair has been proposed, which contains modular hardware configuration and multi-modal user interfaces (e.g., touch-screen, joystick, EEG headset, eye-based camera) for facilitating the control and navigation of the RISE wheelchair. The different types of user interfaces and the modular nature of the wheelchair provide a plug-and-play configuration such that users with different physical disabilities can successfully operate the wheelchair without the need for additional software or hardware modifications. The development of the multi-modal user interface for the RISE wheelchair has been informed by prior research efforts as well as by actual wheelchair users with the goal to enhance the ease-of-usage and operability of the rehabilitative platform. Effort has also been made in order to enhance the ease-of-usage and comfort level of the wheelchair users so that users can traverse from one point to another without facing discomfort or difficulty toward the control and navigation of the wheelchair.

The RISE wheelchair provides an ideal research platform in the field of Assistive and Rehabilitation Robotics. There are a number of different ways to improve the existing model of the RISE wheelchair. One of the ways in which this can be accomplished is by improving the performance and efficiency of the existing implementation. Since, the existing testing of the RISE wheelchair has been conducted in indoor environments, the future works should focus toward improving the coverage, robustness, and practical utility of the system in outdoor environments. While any existing software and hardware deficiencies will also be improved for enhancing the performance of the RISE wheelchair platform in varying indoor and outdoor environments.

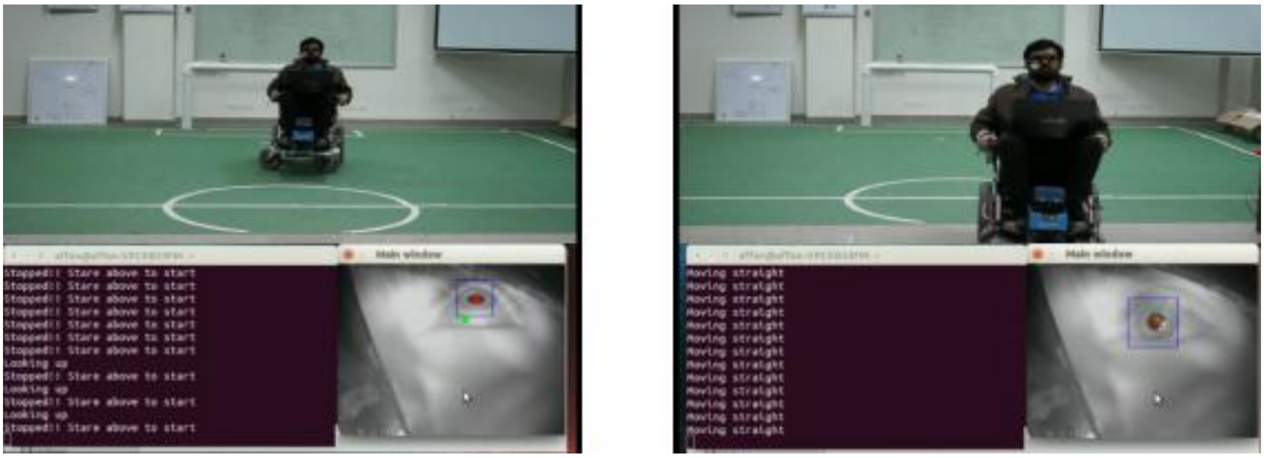

Figure 6. One of the authors driving wheelchair using eye-based user interface

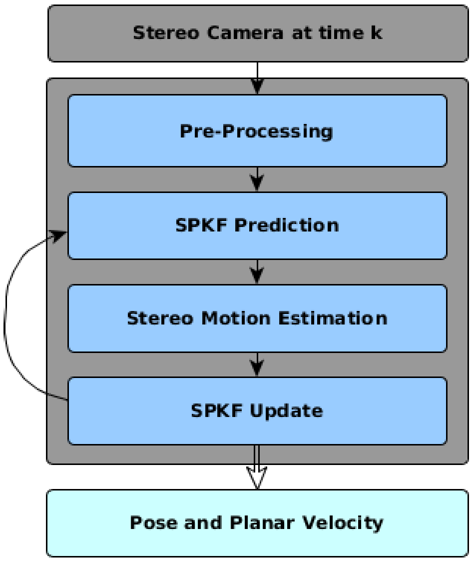

Figure 7. Proposed and implemented strategy for localization

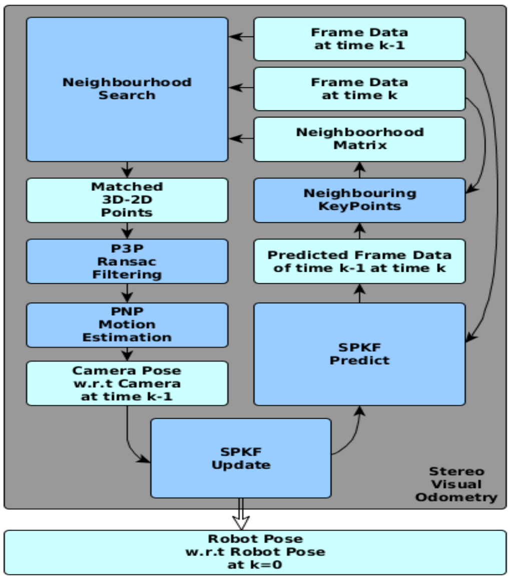

Figure 8. Flowchart for the Stereo visual odometry in the RISE wheelchair

```
Require: Map with information: origin, resolution
Require: Pose of the Robot in world
Require: a boolean Input from user either true or false which increments an integer
  UserInput upto 3 and reset.
Require: A time based boolean input T which switches After every two seconds
Require: state of Wheelchair either Moving or Stopped.
  while No exit command received do
    if Map not updated or loaded then
      Load and Convert Map into gray scale image matrix MapImage
    end if
    if Pose of Robot available then
      Update Pose
    end if
    if state = Moving AND Input = true then
      Send stop command to Wheelchair
    else if UserInput = 0 then
      Draw a line from top left corner of MapImage with origin at P_O
      Move line a step in clockwise direction with origin at P_O
      Save corner point to P_C
    else if UserInput = 1 then
      Draw a circular indicator at P_O and move it in between P_O and P_C
    else if UserInput = 2 then
      Stop the circular indicator at P_G
      if (T = true)
            Decision := GO
      else if (T = false)
            Descision := Cancel
    else if UserInput = 3 then
      if (Descision = Cancel)
            Reset UserInput
      else if (Descision = GO)
            Send navigation goal P_G to wheelchair base
            Reset UserInput
    end if
  end while
```

Figure 9. Pseudocode for the goal selection algorithm

In view of the state-of-the-art algorithms, the system's hardware specifications can also be improved in order to allow the implementation of algorithms that can facilitate enhanced capabilities of the RISE wheelchair toward localization, navigation, and mapping in various indoor and outdoor real-world environments.

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