Development of GenNav: A Generic Indoor Navigation System for any Mobile Robot

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Abstract— The navigation system is at the heart of any mobile robot. It consists of both the SLAM and path planning units, which the robot utilizes to generate a map of the environment, localize itself within it and generate a path to the destination [7]. This paper describes the conceptualization, development, simulation and hardware implementation of GenNav a generic indoor navigation system for any mobile aerial or ground robot. The hardware actuators and software computation units are modularized and made independent of each other, by providing an alternate source of odometry from the Lidar. Hence the actuators used for locomotion are no longer required to carry their own source of odometry and system can be generalized to a wide variety of robots, with different type and orientation of actuators.

Keywords— SLAM, AMCL, Dynamic Window Approach, Dijkstra’s algorithm, Range flow technique for odometry estimation.

I. INTRODUCTION

Autonomous Mobile Robots are increasingly becoming prevalent in recent times, robots are tending towards becoming ubiquitous with their wide range of applications. The navigation system is at the heart of any mobile robot, it performs two interconnected tasks of SLAM and Path-Planning that work synchronously with the hardware.

The hardware actuators are continuously controlled and their feedback is monitored through the Navigation system software. This paper deals with the implementation of GenNav a Generic Navigation System which can be implemented on any mobile aerial or ground robot for indoor navigation. The working of GenNav is independent of the type (Dc, Servo, stepper, BLDC motor etc.), orientation and position of actuators used in the locomotion of the robot. The idea has been previously explored in the form of GeRoNa [2] which is Generic Navigation framework for wheeled robots. GenNav proposes a novel approach for navigation which is not limited to wheeled robots but can also be extended aerial vehicles.

The key requirement for such a system to work is the independence of hardware actuators and the software computational units. The independence and modularization of hardware actuators and software components, in a broad sense can be achieved in two ways. Firstly we can break open the feedback path from the hardware, and secondly we can provide an alternate source of feedback from the existing sensors which are used for scanning such as the Lidar or Camera. The latter would be the better choice as the first choice would create an open loop system which is unreliable and intolerant to noise.

ROS (Robot Operating System) has been extensively used in the development of this navigation system. Here simulations have preceded the hardware development and for the purpose of demonstration we chose to implement GenNav on a Custom designed differential drive robot and on a UAV (Unmanned Aerial Vehicle) which is a quadrotor in this case shown in Fig1.

Fig1: Mobile Robots (Differential Drive robot and quadrotor) on which GenNav has been implemented.

II. ARCHITECTURE OF A MOBILE ROBOT

This section deals with the conceptualization and development of the GenNav. A detail explanation of the integration, data flow and working of various layers in the navigation system is provided below.

a. MECHATRONIC ARCHITECTURE

The Mechatronic architecture describes integration of the sensors, computation, control and actuation of a mobile robot. The interconnection between various layers of a traditional mobile robot is shown in Fig2.

At the lowest level we have the sensors which are used to perceive the environment in which the robot operates. Sensors such as Lidar or 3D-Camera such as a Kinect or Stereo camera which capable of determining the distance to the nearby obstacle and constructing a 3D view of the environment is present in this layer.

The Computation layer performs tasks of obtaining the data from the sensors and providing the necessary commands to the embedded system that controls actuation. An Ubuntu Operating System with Robot Operating System (ROS)
Fig2: Mechatronic Architecture of a Navigation system in a Mobile Robot

installed is used in this layer. The Navigation process can be broadly split into two tasks i.e. SLAM and Path Planning [7], the computational requirement and the feedback monitoring of these tasks is met by the computation layer.

The actuation control layer comprises of an embedded system that processes the commands received from the computation layers and forwards it to the actuators. It is also one of the channels for the feedback from actuators to reach the computation unit.

The computational layer remains unchanged with the use of GenNav. Since the feedback of the actuators action reaches the computational layer through the sensors, the actuation control layer no longer needs to process the feedback from actuators. Thus, there would be no feedback between the actuation control and computation Layer.

b. Software Architecture

This section provides a detail description of the “OS and Computation Layer”. This layer accepts inputs from the URDF (Unified Robot Description Format) a file which describes the structural arrangement of the robot and the Laser scan data from Lidar. Fig3, illustrates the architecture of the “OS and Computation Layer”. The TF is obtained from URDF consist of the necessary transforms between the Lidar, Base and Odometry frames.

SLAM (Simultaneous Localization and Mapping) is the process of generating a Map of the environment in which the robot operates and simultaneously localizing itself within the generated map. The process of mapping requires human supervision, a human operator would guide the robot through the environment and the Lidar scan data would be used to generate the map of the surroundings. Localization is the task of determining the position of the robot relative to the existing map [7].

Mapping is performed using Gmapping which deploys a particle filter based approach along with Rao-Blackwellized Particle Filters [3] and the AMCL which stands for Adaptive Monte Carlo Localization [6] is used to implement localization of the robot within the map , AMCL also uses particle filters for localization.

The Laser scan to odometry is the most important component of GenNav. Here Lidar data is used to obtain Odometry information, thus making the navigation system independent of odometry sensors in the hardware such as encoders and IMU. The conversion of laser scan to odometry is performed using the range flow approach [1]. Here a motion estimate is obtained by minimizing the robust function and the range flow constraint equation is determined in terms of the sensor velocity.

The goal of Path-Planning is to determine an optimal path from source to destination. ROS provides for two path planners, a Global Path-Planner and a Local Path Planner. Generating the path towards the goal from the existing position is the task of the global planner [10]. The local planner is mainly concerned with the obstacles that are there in the immediate surrounding of the robot [9]. It ensures that the robot can safely navigate between obstacles without any collisions.

Odometry data along with the SLAM results are used by the local and global path planners to perform path-planning. We use Dijkstra’s algorithm as the global planner [10] and DWA (Dynamic Window Approach) for the local path planner [9]. The planners are supported with “costmaps”, which are maps where the boundaries of the obstacles are inflated. The global and local costmaps is used by the global and the local planners respectively. The costmaps help in generating a collision free path-plan and ensures optimal route from source to destination.

The integration of the global and local planners with its corresponding costmaps is performed by Move_Base within ROS Navigation stack. The result of this computation process is the actuation signal which is a velocity command that would be fed into the Actuation control Layer.
a. Actuation Control Architecture

The intention of the actuation control system is to obtain the target actuation velocity output equal to the reference velocity command.

![Fig4: Actuation control Architecture](image)

Fig 4, describes the working of the actuation control layer. Here we have implemented a two-step actuation control sequence comprising of the High Level and Low Level controllers. We can observe that the feedback route consists of the Lidar sensor and the odometry is obtained through Laser scan to Odometry conversion.

The locomotion of the robot in space can be governed by its kinematic and dynamic models, these models are implemented in the Low Level controller. The value $v_r$ is the velocity command obtained from the computation layer and $v_o$ is the actual velocity of the robot obtained from the odometry data.

The low level controller implements inverse kinematics/dynamics to convert the velocities in robot reference frame to equivalent individual actuator input $u_{xi}$ where $i$ refers to the $i^{th}$ actuator i.e. $i$ takes 2 values in case of differential drive robot and 4 values in case of a quadrotor. Within GenNav the Low Level Controller is the only unit which is specific to the hardware actuator of the robot.

The error $e_i$ is computed for individual actuator and this is passed into the PID controller which in-turn passes the actuation control signal into the $i^{th}$ actuator and the robot moves towards the destination.

III. IMPLEMENTATION

In this section we demonstrate the working of GenNav on a differential drive robot and on the quadrotor, these two robots are used for demonstration purpose as they have different actuator orientation and control mechanism. The simulations have preceded the hardware implementation, ROS supported simulators such as Rviz and Gazebo were used for simulation.

We first go through the implementation of GenNav on the differential drive robot and proceed towards its implementation on a UAV.

A. Navigation of differential drive robot using GenNav: Simulation Results

The simulations were started with the generation of the URDF (Unified Robot Description File). ROS provides simulators such as Rviz and Gazebo, Gazebo is a simulator which represents the real world robot model and is used to implement and test various algorithms, Rviz is a visualizer which provides graphical tools for visualization and interaction with the robot. A Gazebo world is the environment in which the robot operates during simulation.

As seen in Fig 5 a simple gazebo world is constructed with two blocks in and a surrounding wall. The implementation results of GenNav for the navigation of a differential drive robot is shown in Fig 6.

The odometry information is extracted from the on-board Lidar, using the using the Range Flow approach [1]. As described earlier the first process of Navigation is SLAM, where the robot is expected to move around the environment with the assistance of a human operator, generating the Map of the environment and localizing itself within the given map. The map that is being created can be visualized in the Rviz Fig 6 (A).

The task of Localization is accomplished using AMCL, Fig 6 (B) demonstrates the implementation of AMCL for the differential drive robot. We can observe the arrow marks beneath the robot, these are the pose array estimates, which represent the possible position and orientation of the robot. Moving the robot within the generated map can help to increase the accuracy of the localization estimate. Also observe that the boundaries of the obstacles have been inflated this is the global costmap that is generated.
Path planning has been implemented using Move Base within Navigation Stack. The destination location has been published to Move Base, once the goal is set the path is planned and generated using Dijkstra’s algorithm \cite{10} as the global planner and DWA (Dynamic Window Approach) as the local planner. In Fig 6 (C) the generated path from initial to final position is represented by the brown line.

**B. Navigation of UAV using GenNav: Simulation Results**

The simulations for a UAV has been conducted using the URDF of the quadrotor Fig 1. A new gazebo world has been created to demonstrate the indoor navigation of a UAV. The presence of the quadrotor in the Gazebo world can be seen in Fig 7.

GenNav can be implemented on a UAV with a similar process to a differential drive robot with changes in few of the parameters given in \cite{8} and the Low level controller. The drone is moved around the environment to generating a map using Gmapping Fig 8 (A). The Generated Map is used for Localization using AMCL Fig 8 (B). Path planning is implemented using Move Base whose results are shown in Fig 8 (C).
C. GenNav on differential drive robot: Hardware Implementation

After the successful simulation we proceeded towards the hardware implementation. Here GenNav has been implemented on a differential drive robot using DC motors without encoders. The Robot also includes an RPLidar and Jetson TX2 for computation, an Arduino Board is used for actuation control. The differential drive robot constructed is shown in Fig 9.

![Fig9: Robot Constructed for demonstration](image)

The steps followed during simulation were repeated for the hardware implementation, the robot mapped the indoor space in which it should operate using Gmapping, AMCL localization was implemented and Move Base was used for path planning. Fig 10 shows the resulting map which was generated and the goal position being published through Rviz using an interactive maker.

![Fig10: Setting the destination position in the generated Map.](image)

Once the destination is set the path is computed and the robot moves towards the destination by providing the necessary velocity commands through the High Level PID Controller to the DC motors. Fig 11, shows the final point which the robot has reached once it has travelled the path.

![Fig11: Robot reaching the goal](image)

Battery Monitoring and PWM Correction

During hardware implementation we observed that the performance of the robot was severely affected by the decrease in the battery voltage, this was undesirable as the robot could not be used for long hours due to reduction in accuracy. A battery monitoring system was necessary to determine the present voltage levels of the battery and appropriately correct the output of the PID controller which a velocity command expressed as PWM values.

Let us consider a robot which is expected to move with a velocity \( u \) at a PWM value of \( k \), given the voltage level of the battery is \( V \). Then equation (7) provides the necessary equation connecting the above quantities. Where \( \gamma \) is a constant of proportionality.

\[
\begin{align*}
    u &= \gamma \cdot k \cdot V \\
\end{align*}
\]

Let the present battery voltage reduce form \( V \) to \( V' \) whose difference is given by \( \Delta V \), to compensate for this change the PWM must increase form \( k \) to \( k' \) whose difference is given by \( \Delta k \). These changes are represented in equation (2).

\[
\begin{align*}
    \Delta u &= \gamma \left[ \Delta k \cdot V + \Delta V \cdot k \right] \\
\end{align*}
\]

The PWM must be altered such that the velocity does not change, given a change in voltage of the battery \( V \), hence \( \Delta u = 0 \). Writing equation 2 with the above substitution we get.

\[
\begin{align*}
    0 &= \gamma \left[ \Delta k \cdot V + \Delta V \cdot k \right] \\
\end{align*}
\]

Substituting values of \( \Delta k \) and \( \Delta V \) we get:

\[
\begin{align*}
    (k' - k) \cdot V &= -(V' - V) \cdot k \\
    (k' - k) &= -(V' - V) \cdot \frac{k}{V}
\end{align*}
\]
\[ k' = k - (V' - V) \frac{k}{V} \]
\[ k' = k \left( 1 - \frac{(V' - V)}{V} \right) \]
\[ k' = k \left( 2V - V' \right) \] (4)

Equation 4 provides the modified PWM value such that the robot moves with a constant velocity, given a change in battery voltage. This correction incorporated into the actuation control layer.

Using GenNav, the robot could navigate to any point with a maximum error of 10cm, this error is the Euclidean distance \( d_e \) between the center of the robot and the destination point, an angular error \( \theta_e \) of less than 20\(^\circ\) was obtained, when measured with reference to the line “P”. Fig 12, depicts the measurement convention used to determine error.

![Fig12: Error Measurement Convention used](image)

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