Technical Design Paper Template for the Robotics Dojo Competition 2024

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Abstract-This technical design paper presents the development of a ROS2-based LiDAR mapping robot for the Robotics Dojo competition, where teams compete in mapping and navigation tasks on a dynamic course. The primary aim of the project was to design a robot capable of efficient real-time mapping and autonomous navigation using LiDAR and the ROS2 framework. The robot's system integrates sensor data with SLAM algorithms for environment mapping and path-planning techniques for navigation. Initial testing demonstrated reliable performance in generating accurate maps and navigating obstacles. Our findings highlight the effectiveness of sensor calibration and algorithmic tuning in improving mapping precision and reducing navigation errors. These results offer valuable insights for future design iterations and contribute to the broader field of autonomous robotic systems.

I. INTRODUCTION

The purpose of the Robotics Dojo competition is to enhance the community of innovators capable of substantive contributions to the domain of autonomous unmanned systems. This enhancement is achieved by providing a venue and mechanism whereby the practitioners of the autonomous systems community may form new connections and collaborations, increase their proficiency and inventiveness, and foster their passion for robotics in the maritime domain.

II. PAPER CONTENTS

A. Design Strategy

Our team's approach to the Robotics Dojo competition is centred on balancing advanced capabilities with system reliability, ensuring high performance in mapping, robot control, and navigation tasks. The primary aim is to implement robust LiDAR-based mapping and efficient control mechanisms that allow the robot to navigate dynamic environments with precision. This strategy requires deliberate trade-offs between system complexity and robustness, ensuring that the design remains reliable even under demanding conditions.

For our Control and System Design Strategy we selected the STM32 microcontroller over Arduino due to its advanced features, such as Direct Memory Access (DMA) for fast data reception and an encoder mode, which significantly improves differential drive control. The use of the STM32 allows for precise encoder readings, essential for accurate robot odometry. This is especially important for efficiently navigating sharp corners on the game course and ensuring precise path-planning. Integrating the STM32 for control helps achieve a smoother robot drive and more efficient cornering during the competition, while also providing a foundation for precise motor control in real-time.

However, this decision comes with the challenge of building our own custom control and interface node to bridge the STM32 with the Raspberry Pi, which runs the ROS2-based LiDAR mapping and navigation stack. Despite the increased complexity in creating this interface, the trade-off is justified by the significant gains in motor control precision and overall navigation accuracy. Additionally, the integration of an IMU (Inertial Measurement Unit) enhances odometry, allowing us to achieve more reliable positioning and mapping by compensating for errors and drift in encoder readings.

For our Trade-offs given the competition's time constraints, our approach prioritises refining core functionalities—LiDAR mapping, robot control, and path-planning—before adding any additional sophisticated features. By focusing on reliability first, we aim to ensure that the robot operates efficiently and consistently under competition conditions, reducing potential failure points during critical moments.

While adding complexity through sophisticated capabilities could enhance performance, the risk of introducing new failure points increases. For instance, multi-sensor fusion might provide more information, but they can also affect the system's robustness. Therefore, we have chosen to simplify the sensor integration and data processing, focusing on refining the existing LiDAR and SLAM algorithms. This approach reduces the risk of hardware and software malfunctions while ensuring accuracy and speed in both mapping and navigation tasks.

To further enhance system reliability, we've opted for a low robot height, limiting it to 20 cm 10 cm less than the robotic rules maximum, which optimises the centre of gravity and improves LiDAR stability during navigation. A lower profile also helps prevent tipping when cornering at higher speeds and ensures better manoeuvrability in tight spaces. This design choice also minimises the impact of potential environmental obstacles, reducing the chances of failure due to physical interference during the competition.

Our design choices reflect a careful balance between capability and robustness, as well as reliability and complexity. The use of STM32 for precise motor control and odometry, alongside the ROS2 LiDAR mapping system, allows us to optimise core functionalities without sacrificing reliability. By dedicating our preparation time to testing and fine-tuning these systems, we aim to ensure that our robot is well-prepared for the competition's dynamic challenges and performs consistently in mapping and navigation tasks.

B. Vehicle Design

Our design process began by carefully identifying the key constraints across mechanical, electrical, and software components. These constraints were crucial in shaping our design choices and ensuring that the robot would operate reliably under competition conditions.

Mechanical Design Constraints

From a mechanical perspective, one of our primary considerations was minimising the robot's height to 30 cm. This low-profile design improves stability and reduces the chance of the robot tipping when navigating corners at high speed. To ensure that the LiDAR would function accurately, we had to eliminate disturbances caused by tilting and jerking. We observed that torque effects from the motors could cause the front of the robot to lift, distorting the LiDAR data. To counteract this, we mounted the LiDAR toward the rear and added a counterweight to balance the torque, stabilising the robot during operation. Additionally, the MPU6050 IMU was strategically mounted near the centre of rotation, ensuring accurate yaw measurements.

Electrical Design Constraints

Our electrical design aimed at ensuring sufficient power delivery to all components from a single 20V 37Whr battery. We used an LX540A buck converter to regulate power efficiently, providing 5V for the STM32 microcontroller and 5V 5A for the Raspberry Pi. Additionally, the motors were powered by 12V from the same battery. This power distribution was carefully designed to prevent power shortages and ensure consistent performance throughout the competition.

Software Structure

The software design is divided between the STM32 microcontroller and the Raspberry Pi. The STM32 handles motor control, using PID to manage speed and execute commands received from the Raspberry Pi via serial communication. We utilised DMA (Direct Memory

Access) for serial communication to save processing time, while the encoder mode on the STM32 allowed for precise encoder readings. The STM32 periodically sends motor speeds and encoder counts to the Raspberry Pi, where this data is used for calculating odometry. The Raspberry Pi processes the encoder data and combines it with IMU readings using an Extended Kalman Filter (EKF), ensuring accurate odometry. This odometry data is then integrated into SLAM Toolbox, which works in tandem with the LiDAR to handle mapping and navigation tasks.

Lessons Learned from Design Iterations

Throughout the design and testing process, we encountered several challenges that shaped our approach:

1. **Mitigating Motor Torque Effects**
   One of the significant challenges we faced was the motor torque causing the robot to lift and distort LiDAR readings. We iterated on our design by adding counterweights and repositioning components to better balance the system. This reduced jerking and improved the stability of the robot during navigation, ensuring more accurate LiDAR data collection.
2. **Soft Starting Motors**
   Another lesson learned involved the motor startup process. We implemented a soft-start mechanism to prevent sudden jerks during motor initialization. This improved overall control and reduced the wear on mechanical components, particularly during rapid acceleration or changes in direction.
3. **Documentation and Version Control**
   Proper documentation and version control were essential to our iterative design process. As we refined both hardware and software components, detailed logs of changes and the use of version control tools allowed the team to track progress and revert to stable configurations when necessary. This practice improved collaboration and consistency across the team.

Algorithmic and Software Insights

Motor Control and Communication
The STM32 microcontroller was selected for its DMA capabilities and encoder mode, which allowed us to implement efficient motor control with precise encoder feedback. This setup enabled real-time control over motor speeds and accurate odometry calculations. The use of DMA for serial communication reduced the overhead on the STM32, ensuring that data could be processed and transmitted efficiently to the Raspberry Pi.

Odometry and SLAM Integration
On the software side, integrating encoder data with IMU readings using an EKF significantly improved the accuracy of our odometry. This was critical for maintaining precise navigation and localization during the competition. SLAM Toolbox, running on the Raspberry Pi, used this odometry data to generate real-time maps and navigate the robot through the competition environment. This combination of accurate sensor fusion and reliable control algorithms provided a strong foundation for our robot's performance.

Future Recommendations

For future iterations, we recommend further refining the integration between the STM32 and Raspberry Pi, potentially exploring more advanced motor control algorithms or real-time feedback loops to improve responsiveness. Additionally, early testing of hardware configurations, such as motor torque balancing and sensor placement, will help prevent issues that could arise during the competition. Finally, consistent use of version control and detailed documentation should continue to be a priority to ensure smooth design iterations and knowledge transfer to future team members.

C. Experimental Results

Our team has employed both simulation and real-world testing to validate the design and performance of our robot. For simulation, we modelled the robot and created a URDF of the full assembly, which was then used in Gazebo and RViz for simulating mapping and navigation. Initially, the simulations revealed an issue with torque reaction, where the front of the robot would lift, distorting the LiDAR-generated map. This problem was solved by modifying the distribution of part weights in the simulation, making the front of the robot heavier, which balanced the robot and stabilised the mapping process.

During real-world testing, we encountered similar map distortions caused by LiDAR positioning. To resolve this, we repositioned the LiDAR further toward the rear of the robot and switched it to sensitivity mode rather than standard mode. This adjustment significantly improved the map quality, especially when using the Cartographer SLAM system, which relied on LiDAR odometry. We found Cartographer to produce more accurate and reliable maps compared to SLAM Toolbox, which depended heavily on wheel odometry and was more prone to errors caused by wheel slippage or uneven terrain.

For motor control, we initially approached PID tuning through trial and error. This process involved adjusting the proportional, integral, and derivative gains until the robot exhibited stable and responsive control. To further enhance control performance, we incorporated a moving average filter into the control loop. This filter helped mitigate integral windup, which had previously caused spikes in motor speed that were difficult to control. By smoothing out these unwanted fluctuations, the motor control system became more reliable, resulting in smoother acceleration and deceleration.

In terms of reliability and robustness, our team has focused on testing the robot's ability to maintain stable mapping and navigation under various conditions. This includes subjecting the robot to rapid turns, changes in terrain, and varied speeds to assess how well it can handle different scenarios without compromising map accuracy or losing localization. We continue to refine our system based on these tests, ensuring that it can reliably perform the core tasks of mapping and navigation during the competition.

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