Boston University Electrical & Computer Engineering

EC463 Capstone Senior Design Project

Problem Definition and Requirements Review

Semi-Autonomous Ground Vehicle Convoy

Submitted to

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by
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Client Sign-Off ____________________________________

Semi-Autonomous Ground Vehicle Convoy

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Project Summary

The nature of the Draper Convoy project is to design vision-aided perception and control algorithms for a fleet of Draper’s TurtleBot 4 robots to have semi-autonomous convoy abilities. Each bot must have its own visual feed to recognize and track other members of the convoy and a leading bot, vehicle, or human. These bots must use their visual-aided feed to identify safety threats and to adjust their speed from such threats or changes in the convoy’s movements. Although the bots will act as a convoy, each bot will act semi-independently based on obstacles and other members of the convoy's movement.

1. Need for this Project

With human-robot collaboration becoming increasingly prevalent, there is a pressing need for these autonomous systems to become more robust and autonomous. In certain operational environments such as military, emergency response, or logistics, the ability to coordinate and control multiple robotic vehicles semi-autonomously is critical to reducing human risk and improving overall efficiency.

An autonomous convoy removes the need for an operator for each vehicle and in turn, reduces the chance of human error and increases the potential of a single operator. In a military and defense context, convoys often traverse dangerous or unpredictable terrains where human involvement increases exposure to threats. Autonomous systems that can independently recognize and track their convoy members, while maintaining safe driving behaviors and avoiding obstacles, reduce the risk to human lives and increase operational efficiency. Beyond defense, industries such as emergency response and agriculture can greatly benefit from semi-autonomous convoys. In emergency scenarios, where time and safety are paramount, autonomous convoys could transport critical supplies through debris-laden or hazardous environments. Similarly, in agriculture, autonomous convoys can streamline operations by transporting goods across large farms with minimal human oversight, improving productivity in often labor-intensive processes.

The concept of a semi-autonomous ground vehicle convoy has vast potential across countless applications beyond those already mentioned, thanks to its scalability and practicality. Our Semi-Autonomous Ground Vehicle Convoy Senior Design Project aims to deliver a small-scale proof of concept, demonstrating key convoy capabilities primarily through vision-based perception. The project will feature robust autonomous driving behaviors that adjust to the speed and distance of a tracked leader, while safely detecting and avoiding obstacles to stay within the convoy. This system, implemented with TurtleBot4 for smaller-scale operations, could serve as a foundation for scaling up to larger and more complex vehicles.

2. Problem Statement and Deliverables

We want to design vision-aided perception and control algorithms for a semi-autonomous convoy of TurtleBot 4 robots. Each robot will need to use its video feed from its equipped sensors to autonomously recognize and track other robots that are in the convoy, a designated human leader, and/or a designated lead vehicle. The robots will also each need to demonstrate robust autonomous driving behaviors. They should be able to adapt to the speed and distance of their tracked leader, all while safely detecting and avoiding obstacles while remaining with the rest of the convoy. We hope that upon completion of this project we will have introduced greater levels of autonomy to the devices while keeping them safe and productive.

The deliverables for this project are as follows. The TurtleBot robots have sensors that need to be well calibrated to accurately measure data and effectively avoid obstacles, recognize targets, and track other convoy members. We will have implemented automated target recognition (ATR) using transfer learning from deep networks, vision-based filtering of ATR false positives and overlapping detections, and image segmentation. Our ATR system will need to output a bounding box around recognized targets, along with a confidence level for each detection. Using computer vision and other sensor information, the tracking system will output an estimate of the position and velocity of each object's center of mass once detected by the ATR system. We plan to take advantage of the TurtleBot's onboard vision and LIDAR sensors to determine obstacle distance and use this information to avoid such obstacles. Motion primitives will be used in conjunction with the visual detection and path planning systems to govern wheel movement. This system should allow the robots to achieve follow-the-leader driving behavior while remaining safe, robust, and energy efficient. It is crucial that all of the systems work with one another to have a functional product. To achieve this goal, we will use the Robot Operating System to share information and commands across the different systems within each robot, and potentially extend this communication to other members of the convoy. To ensure that everything works as expected, each of our systems will be rigorously tested before and after we integrate them into the complete system. This testing should allow us to identify failure points, improve fault tolerance, ensure the system's usability, and measure performance. Periodic testing as we implement should ensure that each of the implemented systems is working properly before adding and/or connecting them to others.

3. Visualization

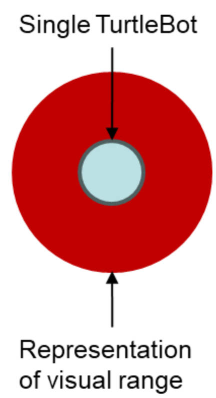

Figure 1.1 This is an example of a single turtle bot and what it will look like in Figures 1.2-1.4.

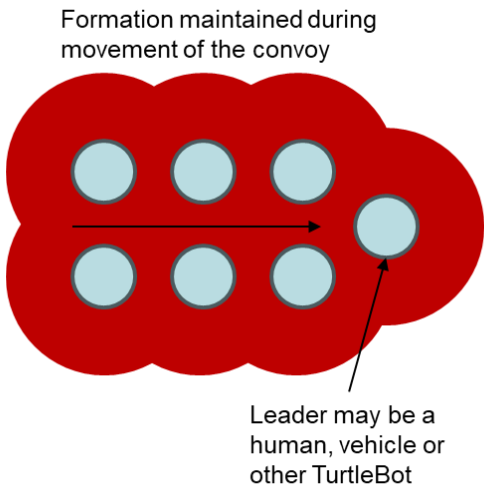

Figure 1.2 This figure represents the swarm capabilities of the TurtleBot, able to stay in formation during movement and maintain speed as set by the leader and seen by other TurtleBots or other vehicles in the convoy.

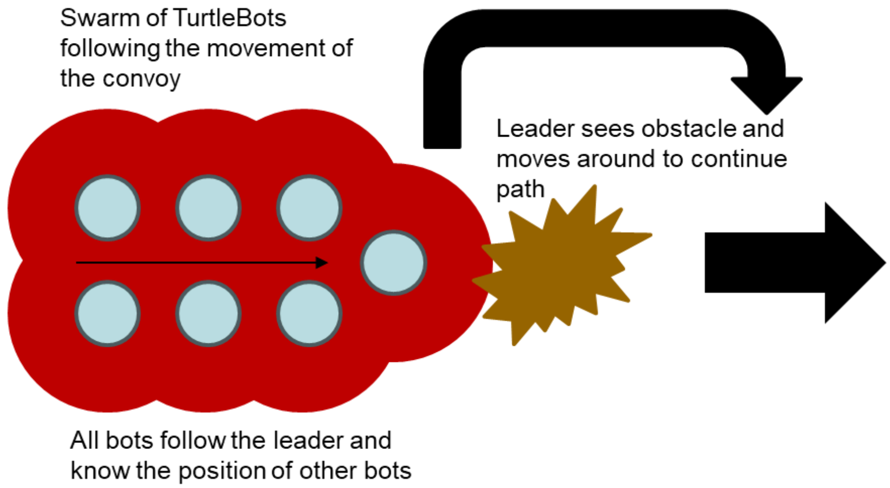

Figure 1.3 This shows how a swarm of TurtleBots should be able to move in formation while avoiding obstacles, the leader sees the obstacle first and will move around it, the next row follows the leader, and the following rows will move with the bots/vehicles in front of them.

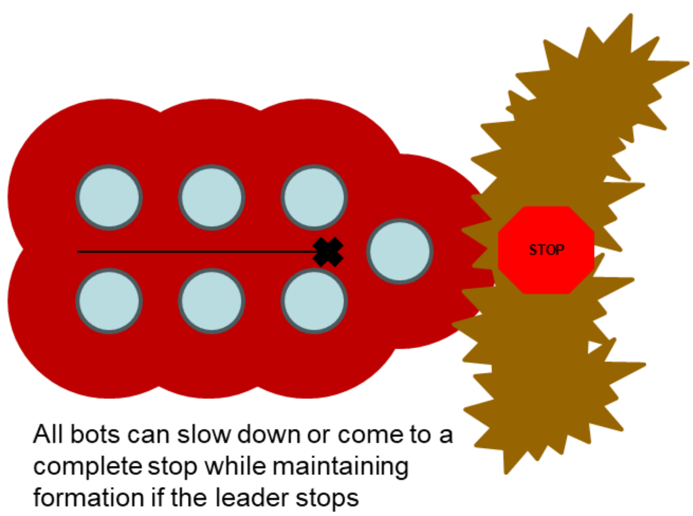

Figure 1.4 This shows an example of the ceasing of movement from the swarm. If an object is found to be impassible, the convoy can come to a stop or slow down while staying in formation.

4. Competing Technologies

During our initial investigation of this Semi-Autonomous Ground Vehicle Convoy project, we looked into competing technologies that contain similar requirements and address similar challenges in order to gain insight into our own task. It helped us gain a better understanding of the general technical landscape of autonomous ground vehicle technology.

Here are some of the competing technologies we found:

IRobot Roomba:

An autonomous vacuum cleaner. Although the objective is slightly different than ours, the requirements have similarities: the robot has to avoid obstacles - more specifically, have the recognition technology and learning capabilities to do so.

We would be incorporating the same objection avoidance principles in our own design. The Roomba only has to avoid objects in the room, but our autonomous robot convoy has to avoid obstacles in our path space and *additionally* take care to avoid collision with other robots in the convoy.

The Roomba in particular is designed for small room usage, and it is able to take advantage of this by mapping the room with its infrared sensors before any cleaning is performed. Depending on the terrain and scale of the environment our convoy will be operating on, we can choose to include pre-mapping functionality to our spatial detection process, if the size proves to be too large then en route mapping may be the only option.

Lastly, the Roomba involves some user interaction options. Users can turn the device off, turn it on, change settings, etc. This is another aspect we have to consider with our project. Is our convoy system meant to be *completely* autonomous, i.e., no human interaction with the robots from the initiation of the robots on their paths to termination, or should we have some human-influenced settings?

Tesla Robotaxi:

A service in the works, Robotaxi is an autonomous vehicle designed for public transportation. While its primary goal is transporting passengers autonomously, many of its requirements align with those of our autonomous robot convoy, particularly in terms of real-time navigation, obstacle avoidance, and interaction with both moving and stationary objects in the environment.

Like our convoy, the Robotaxis will be using an obstacle detection system, although their implementation will have some extra considerations. The Robotaxi system will likely use a centralized GPS algorithm for overall navigation and will need some more functionality for vehicular logic and safety, where it must adhere to traffic rules and ensure passenger safety. In this light, our autonomous convoy is a simpler version of the Robotaxi. Safety is paramount in both projects—Tesla's Robotaxi must prioritize preventing crashes and accidents at all costs to ensure the safety of its passengers, just as our autonomous convoy must safeguard against collisions to protect both the system and its surroundings.

Some of the vehicular features of the Robotaxi can potentially translate to our robot convoy model. The Robotaxis proclaim to have an adaptive cruise control feature, for ease of navigation and speed management. We could look into creating a similar system for our convoy robots, if no obstacles are scanned for a specific distance and the path is suitable, the robots could potentially enter a cruise control mode to maintain a (high) speed.

Additionally, the Robotaxi technology incorporates a "mothership" system, where the taxis revolve around a central charging/loading dock to assemble as well as depart from. In our autonomous convoy setup, there is mention of a potential designated lead vehicle, so similar parent-child constructs may have to be implemented when designing the specifications of our convoy.

5. Engineering Requirements

This section describes the engineering functions to meet required objectives.

5.1 - Control

1. Control systems for the convoy should use communicated path planning and object detection from other system components to govern wheel motion.
2. Motion primitives that govern wheels must allow for safe, robust, and energy-efficient autonomous “follow the leader” driving behavior.

5.2 - Obstacle Detection

1. Integration of sensors such as cameras or lidar, or a combination of the two should be used to determine the system’s distance from obstacles.
2. This information must be communicated to control systems to avoid these obstacles.

5.3 - Automated Target Recognition

1. Each convoy member must be able to recognize fellow convoy members, including the convoy leader, designated human leader, or designated lead vehicle via transfer learning from an existing deep network such as ResNet18.
2. Convoy members should use vision-based filtering of ATR false positives and overlapping detections, prioritizing minimal error rate.
3. Image segmentation may also be used for the purpose of recognizing fellow members, depending on the system as it develops.
4. The ATR system should output a bounding box and confidence level for each detection.

5.4 - Tracking

1. The tracking system of the convoy should output an estimation of the position and velocity of each ATR detection’s center of mass using computer vision, potentially also complemented with other sensor information.

5.5 - Sensors

1. Well-calibrated and thoughtfully chosen sensors are paramount in the implementation of all other engineering requirements.
2. Cameras, lidar, or other sensors will be needed for obstacle detection and convoy member recognition.
3. IMUs, wheel encoders and the like will be needed for motor control, autonomous navigation, and motion primitives.

5.6 - Integration & Testing

1. All components previously mentioned must be integrated into the existing system, TurtleBot 4, and be well-calibrated to carry out objectives.

2. ROS2 may be used as a framework for sharing information and commands between the robots and potentially by extension, the rest of the convoy.
3. Each system/convoy member must be rigorously tested before and after the integration of separate components into the working whole in order to identify failure points, improve fault tolerance, ensure usability, measure performance, and general optimization.

5.6.1 - Additional Behavior

1. Time allowing, this project could also be extended to integrate an open-source simultaneous localization and mapping (SLAM) system, state estimation, or additional swarm/teaming behaviors.

5.7.0 - Constraints

1. The system must be built using the company sponsor budget as well as reimbursement from Boston University, being one thousand dollars.
2. Per client communication and budgeting, the system must operate with a minimum of two Turtlebot 4 Lite robots.
3. Target recognition accuracy and certainty must be above 95%, while minimizing false positives and negatives.

6. Appendix A References.

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