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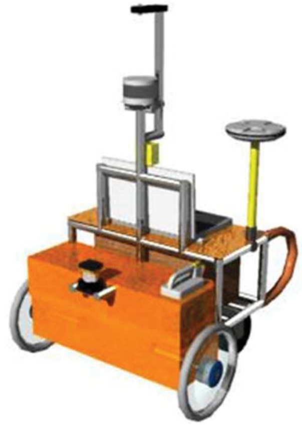

Orange2017

Design Report

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Faculty Advisor Statement

I hereby certify that the engineering design on Orange2017 was done by the current student team, and it is significant and equivalent to what might be awarded credit in a senior design course.

Signed Kazuyuki Kobayashi Date May.15.2017

Prof. Kazuyuki Kobayashi May 15, 2017

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ORANGE2017

Hosei University

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ABSTRACT

This paper describes the development of Orange2017 for participation in IGVC2017. Orange2017 is built on the basis of Orange2015, which was entered into IGVC two years ago. The authors' team result was 11th place overall, 10th in the Auto-Nav Challenge, and 6th in the JAUS Challenge. Based on the experiences gained from the failures encountered in IGVC2015, we have redesigned Orange2017 with overall improvement in performance, mainly vehicle motion stability.

INTRODUCTION

The Hosei University Autonomous Robotics Laboratory (ARL) team has greatly improved the design of Orange2015 to create a new vehicle for participating in the 25th Annual Intelligent Ground Vehicle Competition (IGVC), 2017. Compared to Orange2015, we redesigned and amended both the hardware and software based on team discussions to implement the new concept of intelligent mobile vehicle for participating in IGVC2017. New sensors and improvements in both the hardware and the software of Orange2015 are summarized in Figure 1.

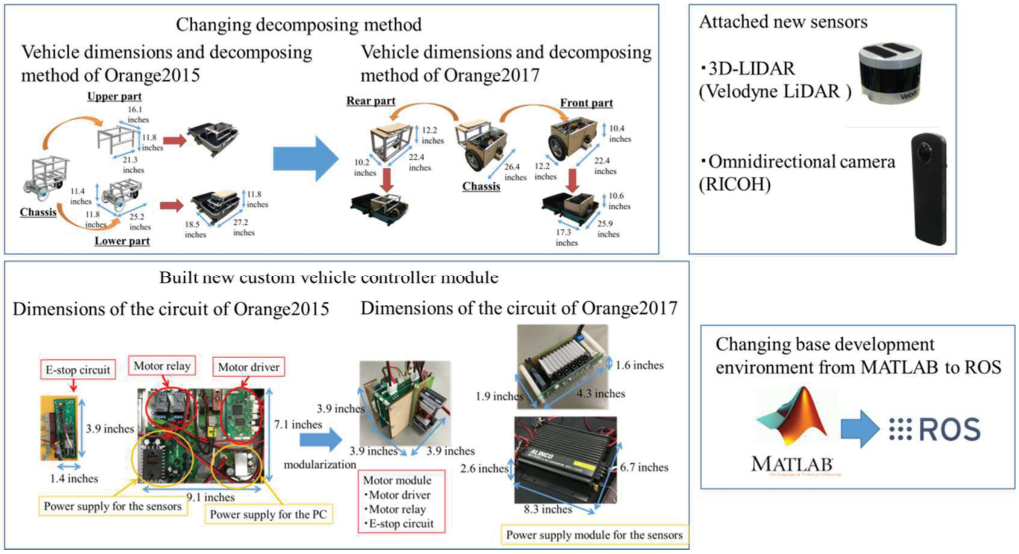

Figure 1. Significant innovations in Orange2017.

The details of these innovations are described in later sections.

TEAM ORGANIZATION

This year, six members are working on this project. The roles of the individual participants and the hours spent by them on the project are summarized in Table 1.

Table 1. Roles of individuals and hours spent by them on project

Role / Team member	Mechanical	Electrical	Software	IOP	Design Report	Hours
Tatsuya Kawano (Team Captain)			○	○		640
Hiroka Shigi			○			320
Tomohiro Shimizu	○	○			○	480
Toshihiro Takahashi			○		○	320
Ryota Nakamura				○		440
Kousei Horichi					○	5

DESIGN PROCESS

In bringing intelligent mobile vehicles from outside the US, transportation is a challenge. One of the solutions is to carry the intelligent mobile vehicle as baggage. However, to this end, we must satisfy not only the IGVC rules but also airlines' baggage rules. To satisfy both requirements, we completely redesigned the existing intelligent mobile vehicle.

Through team discussions, we froze the design concept of Orange2017.

1. Suitcase-aware intelligent mobile vehicle.
2. Motion-stability-aware intelligent mobile vehicle.

To satisfy above two concepts through design, we applied the D-case (Dependability-case) model developed by JST (Japan Science and Technology Agency).

Table 2 shows a typical example of node explanation in the D-case model.

Table 2. Typical nodes of D-case model

Nodes	explanation
Goal	Proposition to be discussed for target Example: Vehicle is safe.
Strategy	How to think about how to expand into subgoals to satisfy goals Example: Think about safety separately in terms of hardware and software.
Context	Information as a premise when we think about goals and strategies Example: Requirements list
Evidence	Things that ultimately support dependability of the goal Example: Test results

The D-case model of Orange2017 is shown in Figure 2.

To build the D-case model for Orange2017, we analyzed the failure incidents of Orange2015 and set the final goal (top goal) as defined "Our vehicle completes the course and wins the competition." To achieve the top goal, our vehicle must satisfy the three requirements shown in Figure 3. They are "Mobile vehicle should be a stable and suitcase-aware," "Mobile vehicle conforms to IGVC rules," and "Improvement of software." These are based on the requirements of IGVC and our analysis of the failure of Orange2015. For satisfying these requirements, we think about points related to hardware, namely, easy maintenance and stability, and about points related to software, namely, the software itself and the software technology to be adopted. Making strategies like these and repeatedly creating subgoals would help us achieve the main goal easily. We finally did the following to achieve the goals: use aluminum flames, fabrication of new custom vehicle controller module, reassignment of payload storage position to a lower place, improvement of vehicle dimension ratio, attachment of new 3D-LIDAR, attachment of additional 2D-LIDAR, attachment of new omnidirectional camera, and changing base development environment from Windows/MATLAB to Ubuntu/Robot Operating System (ROS). The D-case model is conceptualized based on reliability, and its own tree structure shows the reliability of the system.

The requirements of IGVC and the failure incidents of Orange2015 are given in Tables 3 and 4, respectively.

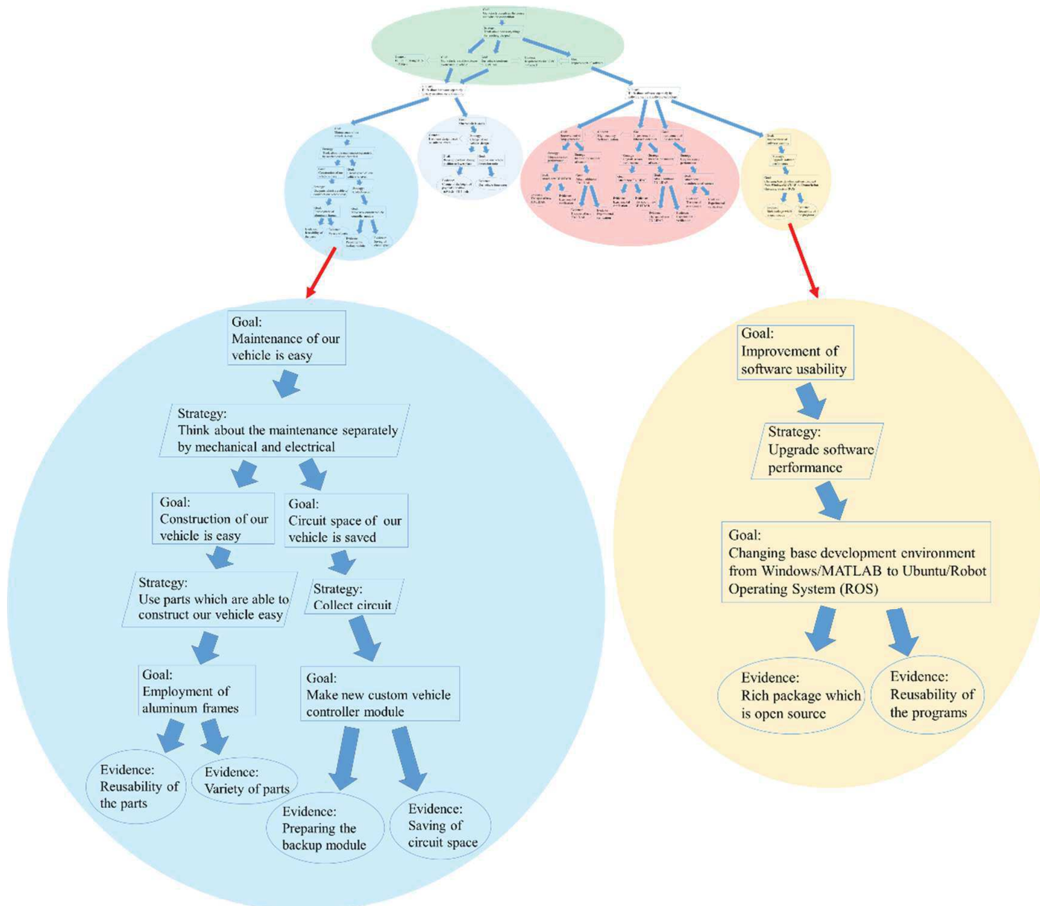

Figure 2. D-case model of Orange2017

Table 3. IGVC requirements

<table>
<tr><th>IGVC rules</th><th>Airline requirements for carried baggage/International team (outside of the United States)</th></tr>
<tr><td>Vehicle design satisfies IGVC rules.
(Length: 3–7 ft, width: 2–4 ft, Height: ~6 ft)
Securing payload space
(Payload size: 18 × 8 × 8 in, Payload weight: 20 lb)</td><td rowspan="3">Vehicle design is suitable for suitcase.
(The total of suitcase length, width, and height must not exceed 62 inches)</td></tr>
<tr><td>・Safety Light
・Mechanical E-stop
(It must be located at a height of 2–4 ft from ground)
・Wireless E-stop
(It must react even from 100 ft ahead)</td></tr>
<tr><td>・Accurate control from 1–5 mph
・Obstacle detection and avoidance
・Goal selection, path planning, and path generation
・Map generation</td></tr>
</table>

Table 4. Failure in Orange2015, causal relationship

Failure in Orange2015 (Cause→Effect)	Solution
･Vehicle width was relatively short compared to vehicle length. ･Payload position was high. →Vehicle tended to tip over when executing sudden changes in driving course.	･Redesign vehicle dimension to take into account motion stability. ･Reassign payload storage to a lower position.

INNOVATIONS

Innovative Concepts from Other Vehicles Incorporated into Our Vehicle

The basic concept of "Suitcase-aware mobile vehicle," which is the same concept of Orange2015, is necessary for carrying the vehicle from Japan to the U.S. In addition, to run the course completely, we improved the stability of our vehicle.

To satisfy the two requirements of suitcase dimension and motion stability of vehicle, we referred to the frame design of Orange2015 and vehicle dimension ratios of other vehicles were entered into IGVC 2016.

Innovative Technology Applied to Our Vehicle

The innovations of Orange2017 are summarized in Table 5. There are five innovations in both hardware and software. One is for vehicle motion stability to satisfy suitcase dimensions. Two and three are for improving vehicle sensing stability to recognize surrounding environment by eliminating dead angle. Four is for vehicle electronic design stability without having to use a wire harness between each discrete module. Five is for vehicle software design stability, which can be achieved by using existing huge external packages.

Table 5. Innovations in Orange2017

Hardware (Mechanical and Electrical)	Software
1. Changed decomposing method to front part and rear part from upper part and lower part 2. Attached new 3D-LIDAR that can monitor 360° surrounding range profile. 3. Attached new omnidirectional camera that can monitor 360° surrounding image profile. 4. Developed new custom vehicle controller module from discrete vehicle modules	5. Base development environment was changed from Windows/MATLAB to Ubuntu/Robot Operating System (ROS).

MECHANICAL DESIGN

Overview

Orange2017 was designed based on the D-case model (Figure 2) by using CAD. As shown in Figure 3, all sensors are attached, PC is installed, and payload is stored.

Figure 3 shows CAD images of Orange2017.

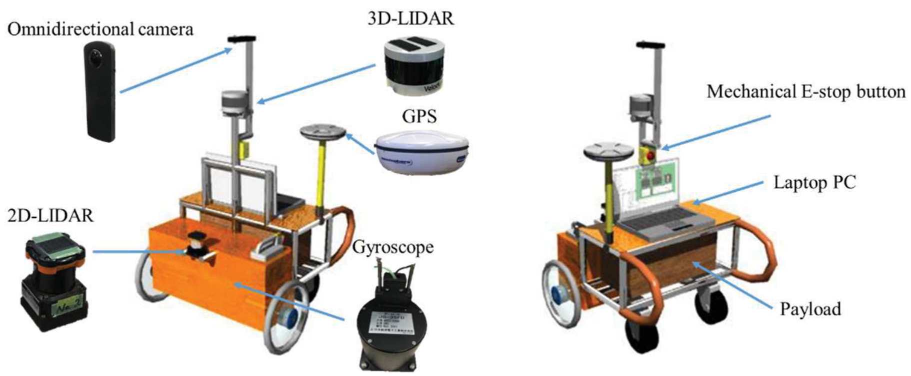

Figure 3. CAD images of Orange2017

To satisfy requirements of suitcase dimension and motion stability, we redesigned frame chassis configuration of Orange2015. Figure 4 shows differences in vehicle dimensions between Orange2015 (left) and Orange2017 (right).

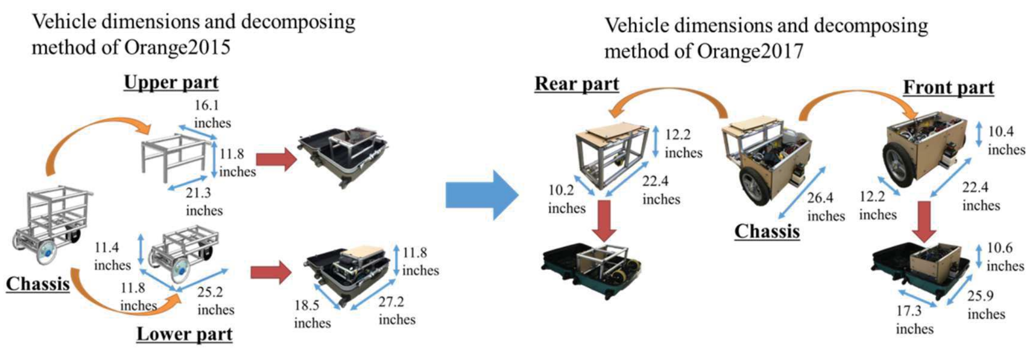

Figure 4. Differences in vehicle dimensions and decomposing method between Orange2015 and Orange2017.

To fit the suitcase dimensions, the vehicle must be decomposed into two components. In Orange2015, we designed the upper and lower components, as shown in Figure 4 (left). However, we found this approach was unsuitable in terms of vehicle motion stability because of tip-over failure during IGVC 2015. To prevent tip-over, we redesigned the front and the rear components, as shown in Figure 4 (right).

Decision about Frame Structure, Housing, Structure Design

Drive chassis, frame structure. The drive chassis and frame structure of Orange2017 are shown in Figure 5. Based on our experience in Orange2015, the same aluminum frame, which satisfied the durability, extendibility, and maintenance ability requirements, was selected for Orange2017.

Considering the design constraint of conforming to suitcase dimensions, Orange2017 was divided into front and rear components.

The front component houses most of the electrical hardware, including the battery, DC/DC converter, and custom vehicle controller module (including motor driver, both E-stop and wireless E-stop) and two motors which are directly connected to the drive wheels.

The rear component houses the payload storage area and a laptop personal computer. For motion stability, two caster wheels are attached to the rear component.

To prevent tip-over when executing sudden changes in driving course, the payload storage space is arranged laterally (perpendicular to the travel direction of our vehicle) instead of longitudinally (same direction as the travel direction of our vehicle).

Figure 5. Drive chassis and frame structure of Orange2017

Exterior and accessories. We designed the exterior and accessories by using CAD.

- Exterior: We selected MDF (Medium Density Fiberboard) for the exterior of Orange2017 because it is light and easy to process.
- Camera mount: This part was designed such that the omnidirectional camera remains parallel to the ground, lens faces the ground, and the mount can be installed on the center pole of Orange2017.
- Fan cover and code cover: As part of weather proofing, we placed the fan's exhaust port for the circuit and the hole cover that will give out the codes in the front part of our vehicle.

The CAD drawings of the abovementioned parts are shown in in Figure 6.

Figure 6. Exterior and accessories designed using CAD

Fans. The omnidirectional camera and circuit, especially the gyroscope, tend to heat up, so we considered the possibility of thermal runaway and breakage, and decided to attach fans for cooling.

Figure 7 shows the fans.

Figure 7. Cooling fans

Weather proofing. For weatherproofing, we fabricated a rain cover by altering a bicycle rain poncho to cover the entire vehicle. The cover is shown in Figure 8.

Figure 8. Weatherproofing cover

ELECTRONIC AND POWER DESIGN

Overview

Figure 9 shows a comparison between the electronics and power design of Orange2015 and Orange2017. As shown in the Figure 9 (left), several electrical components are connected through complicated wire harness. As shown in Figure 9 (right), we built power supply modules for the sensors and the custom vehicle controller module, which drives the motor, LED light control, wired E-stop, and wireless E-stop, to avoid having to use a complicated wire harness. To prevent damage due to vibration caused by driving on rough roads, all modules and sensors are protected by insulating them from the vehicle chassis.

To aid vehicle recovery in the event of electronic module failure, we have installed several backup modules in Orange2017. To shorten recovery failure time during the competition, we will simply replace failed modules without troubleshooting the vehicle. After replacing the failed modules, we will analyze the reason for failure on a desk instead of in vehicle.

Figure 9 shows changes in the dimensions of the circuit of Orange2017 relative to the circuit of Orange2015.

Figure 10 shows the insulators used in the circuit of Orange2017.

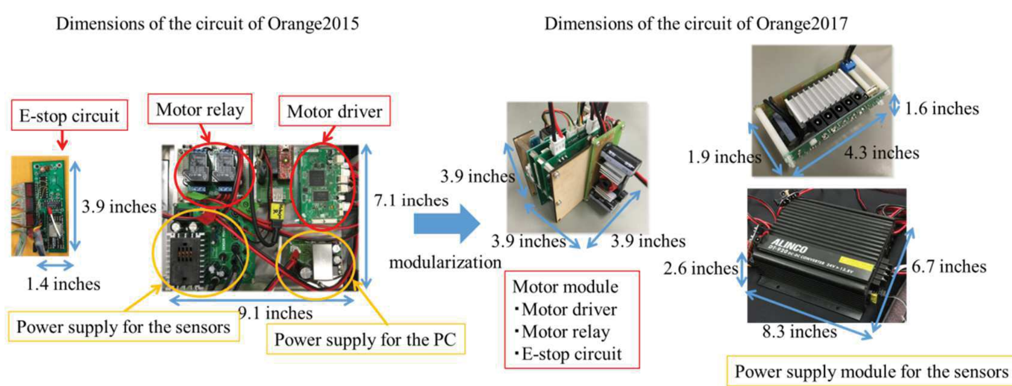

Figure 9. Changes in dimensions of circuit

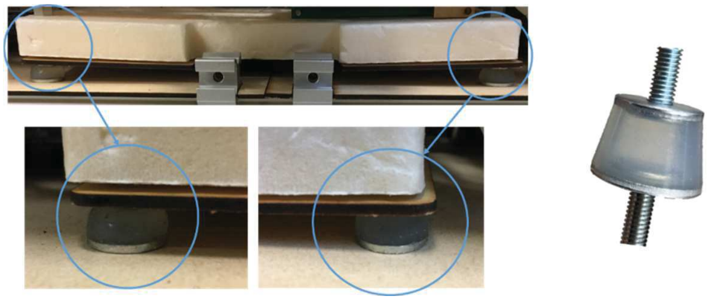

Figure 10. Circuit insulators

Power Distribution System

Figure 11 shows the flow of electronic power and the signal flow configuration in Orange2017. 24 V supplied using a nickel hydride battery to the custom vehicle controller module, which drives the two motors. A DC/DC converter (24 V to 12 V) is used for supplying power to the various sensors and the laptop PC.

The omnidirectional camera is connected to the PC by USB. The 2D-LIDAR and the 3D-LIDAR are connected to the PC by an ethernet cable. The GPS and the gyroscope are connected to the PC by a serial to USB cable.

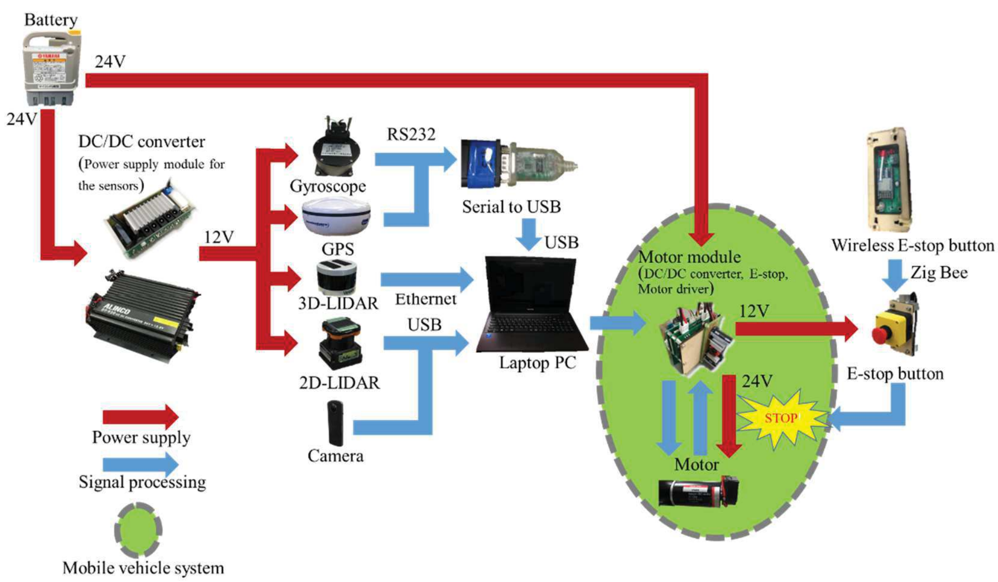

Figure 11. The flow of electronic power and the signal flow configuration in Orange2017

Electronics Suite Description Including CPU and Sensor System Integration

The costs and descriptions of the sensors installed in Orange2017 are summarized in Table 6.

Table 6. Cost and description of sensors

Component	Product name	Team cost (Retail cost)	Description
3D-LIDAR	Velodyne LiDAR VLP-16	\$11,685 (\$11,685)	This sensor collects data over 360° in the horizontal direction, 30° (±15°) in the vertical direction, and from 3.3 to

			328 ft ahead with an accuracy of ±0.1 ft. It is used for map generation and self-localization. The measurement time is 50 ms to 200 ms.
2D-LIDAR	HOKUYO UTM-30LX	$0 ($4,000)	This sensor covers the range of 270° in the horizontal direction, and it can measure from 0.33 to 98.4 ft ahead with an accuracy of ±0.2 ft. It is used for obstacle detection. Measurement time is 25 ms.
Gyroscope	Japan Aviation Electronics Industry JG-35FD	$0 ($5,800)	The measurement range of this sensor is ±200°/s. It is used for self-localization. Measurement speed is 50 ms.
GPS	Hemisphere Crescent A100	$0 ($2,414)	This GPS corresponds to differential correction information, and the measurement accuracy is 1.9 ft. It is used for self-localization. The update rate is 100 ms.
Omnidirectional camera	RICOH RICOH THETA S	$330 ($330)	The memory of this camera is 8 GB. Data is captured by connecting it to the PC via USB. It is used for line detection. Shutter speed is 1/8000–1/15 s.
Laptop personal computer	FRONTIER FRNXW610/C	$840 ($840)	The memory of this PC is 8 GB. The CPU is an Intel® Core ™ i7-4710 MQ.
Motor, gear and encoder	MAXON RE40+GP42C+ HEDL5540	$0 ($1,000)	
Motor driver	Tsuji Electronics TF-2MD3-R6	$0 ($340)	
Mechanical parts		$895 ($895)	
Electronical parts		$445 ($445)	
Total		$14195 ($27749)	

Safety Devices and their Integration into Our System

E-stop capability is closely related to the motor driver circuit. Therefore, we developed a custom vehicle controller module that covers both motor driver function and wired and wireless E-stop.

The E-stop button is shown in Figure 12. When the E-stop button is pressed, the E-stop circuit shuts off power supply to the motor without going through software.

Figure 12. E-stop buttons

The safety light is shown in Figure 13. When the vehicle is powered on and is not in the autonomous mode, it is in the state shown on the left in Figure 13. If the vehicle is in the autonomous mode, it flashes as shown on the left in Figure 13. Then, when the E-stop button is pushed, it changes to the state shown on the right in Figure 13. When the button is reset, it reverts to the state shown on the left in Figure 13.

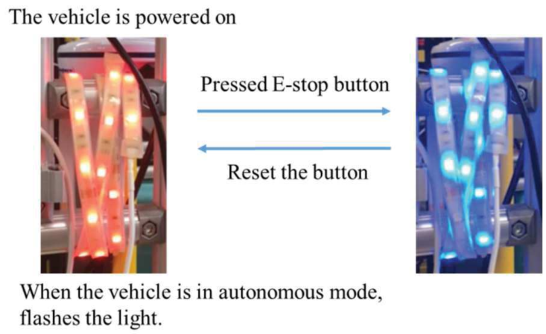

Figure 13. Safety light in both modes

Therefore, our safety devices meet the requirements of IGVC.

SOFTWARE DESIGN

Software Platform

Different from the previous platform, in which we used MATLAB, we have installed a new platform for our vehicle software system, which is ROS (Robot Operating System). ROS operates in Ubuntu, Linux. ROS prepares many preexisting packages such as drivers for often-implemented sensors such as camera, LIDAR, and GPS. ROS also prepares libraries that are open-source packages registered by individuals, and many useful libraries have been produced. We are implementing a library called move_base in our software system. It is a very popular package, and many open-source robot software systems use it. There are many other benefits of using ROS.

Idea and Benefits of Nodes

ROS is comprised of individual software modules called “nodes.” Each node has its own function and operates individually. They are written in C++ or Python. Nodes communicate among themselves by publishing information to “topics” and by subscribing to the topics, nodes can receive information published by other nodes. Inter-node communication can be checked by the entire system.

Debugging

ROS has robust debugging capabilities. ROS creates bag files, and all messages interchanged between nodes, including the times of their exchange, are saved in these files. Therefore, without preparing the vehicle for operation, one can recreate the situation in which the messages were interchanged. Also, the built-in package, reconfigure_gui, contributes to the debugging capability. By using reconfigure_gui, the vehicle parameters can presented in the form of graphical bars. A miniscule change in a parameter has a significant effect on vehicle behavior. Reconfigure_gui makes the calibration of those parameters easier by allowing users to change the parameters while operating the vehicle.

Obstacle Detection and Avoidance

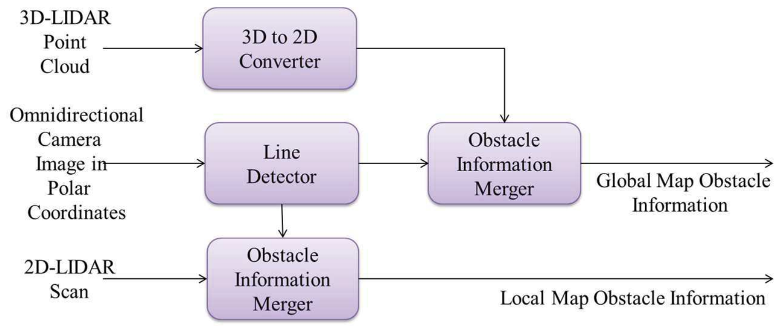

Figure 14. Processing obstacle information

Figure 14 shows how the information from the omnidirectional camera, 3D-LIDAR, and 2D-LIDAR are merged to obstacle information. The white line data obtained from the omnidirectional camera are merged with the 3D-LIDAR and the 2D-LIDAR data to generate obstacle information. The information obtained by merging data of the omnidirectional camera and the 3D-LIDAR is reflected on the global map, and the information obtained by merging the data of the omnidirectional camera and the 2D-LIDAR is reflected on the local map. White lines are treated as obstacles in our system.

Line Detection

As mentioned above, white lines are detected by the omnidirectional camera. To do so, first, we must calibrate image distortion because the filming coverage of the omnidirectional camera is so large that the images are distorted when attempting to fit them in a circle. Then, image thresholding must be performed to classify the colors in an image into black and white. By applying morphology processing at the opening, we eliminated noise. Moreover, we applied template matching. Thereafter, images were converted into polar coordinates, which are used to locate the vehicle in the origin. Using these coordinates, the distance between the vehicle and the white lines can be calculated easily. The line data and the 2D-LIDAR data are merged to form object information (Figure 15).

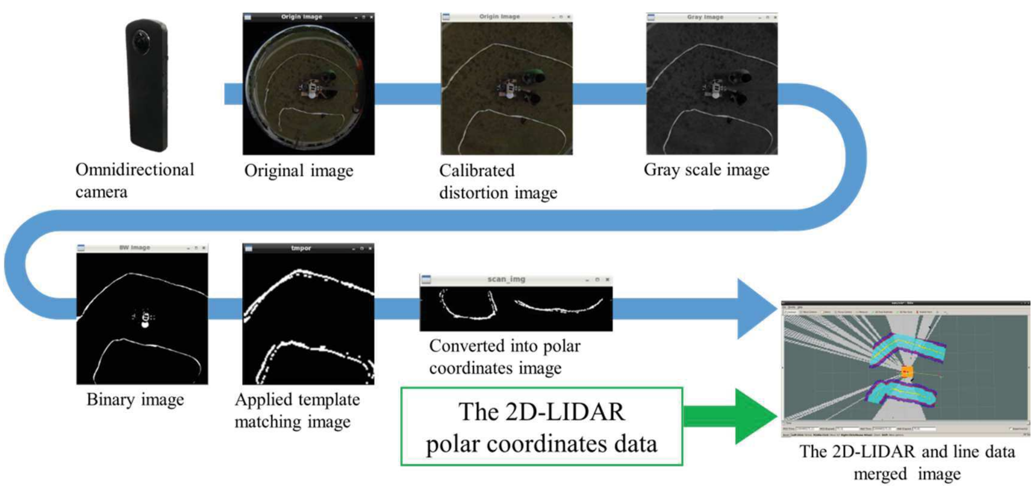

Figure 15. Processing images obtained by omnidirectional camera

Avoidance

For avoidance, environmental obstacles are detected by both the 3D-LIDAR and the 2D-LIDAR. The use of both LIDARs improves accuracy and sensing speed. The avoidance module combines the obstacles detected by the two LIDARs with the lines detected by the omnidirectional camera, analyzes the environmental situation, and generates the shortest and safest path for the mobile vehicle.

Path Planning by Waypoint Navigation

Self-Localization. The mobile vehicle retrieves its self-position from GPS. If the GPS signal becomes unreliable, self-localization is performed by particle filtering based on the data obtained by the 3D-LIDAR and the omnidirectional camera. Self-localization by using the 3D-LIDAR and the omnidirectional camera data is performed by a map-matching technique, in which the mobile vehicle searches a global map for points that match its surrounding local map.

Path Planning. To ensure robust and stable path planning for the mobile vehicle, we employed a potential path-planning method. In the first stage, a local map is created using the 3D-LIDAR data and the lines detected by the omnidirectional camera. In the second stage, the path of the mobile vehicle is generated using an A-star search algorithm. The first and second stages are iterated to obtain a safe and robust path from the current position to the next waypoint.

Map Generation

To generate maps, we used the 3D data obtained by the 3D-LIDAR and converted them into 2D (Figure 16). In the case of objects that differ in size between their lower and upper parts, the size of the part closer to the vehicle is considered as the object size. The map is generated as the vehicle navigates itself toward the destination. Only the white clusters of dots in Figure 16 are reflected on the 2D map as object data. The pale grey area in the generated map in Figure 16 is the traveling possible area, and the dark grey area shows the unidentified area. Even if the navigation fails, the map is saved and is used for the next run. Matching several maps can increase the possibility of getting erroneous data. Therefore, the vehicle uses only the map generated in the previous run. White lines are also registered in the maps as objects.

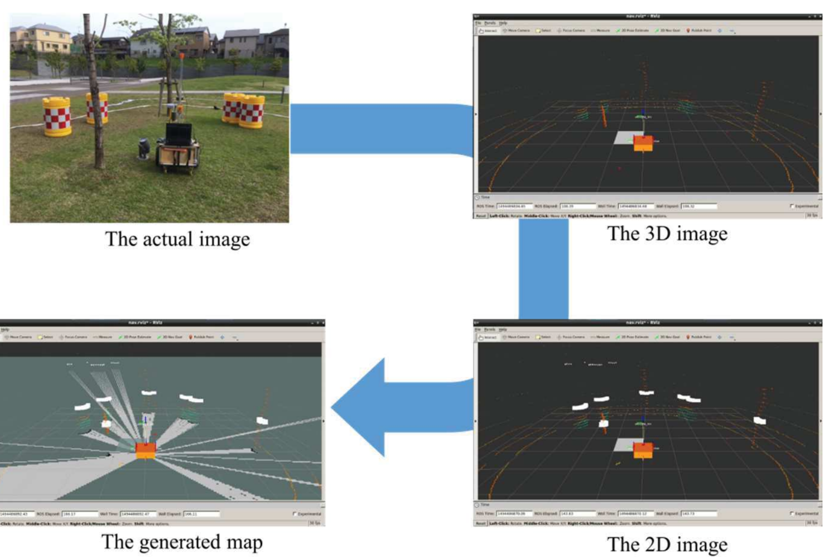

Figure 16. Converting 3D-LIDAR point cloud data into scan data

Goal Selection and Path Generation

Path generation is divided into two functions, namely, costmap generation and path planning. The costmap utilizes cost information, the value of which increases as the vehicle gets closer to the detected objects. The path planner calculates the shortest path to the goal by considering cost information from the costmap. The costmap is of two types, global costmap and local costmap. The global costmap uses global map information to calculate the shortest path to the goal, and local costmaps use local maps.

Path planning is of two types as well, global path planning and local path planning. Both types calculate the shortest path to the goal, but the only difference is that the local path planner refers to local maps and the global path planner refers to the global map. In Figure 15, the yellow-colored-area shows the locations of the objects, and the pale-blue-colored area shows where the vehicle crashes into objects. The blue area shows the locations that the vehicle should avoid if possible, even if it will not crash into an object at those locations. The area indicated by red shows the border between the area of crashing into an object and the area to be avoided if possible. The green line that sticks out from the front of the vehicle is the path generated by the global path planner. The red line that sticks out from the front of the vehicle is the path generated by the local path planner (Figure 17).

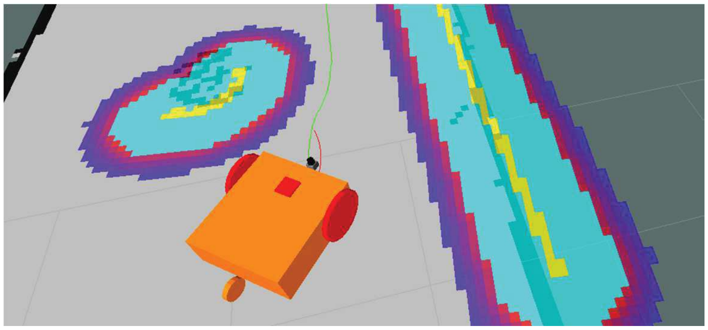

Figure 17. Costmap and path planner

Additional Creative Concepts

Our creative concept for this competition is to make the vehicle recognize white lines as obstacles. For making the vehicle run straight forward, we needed to set virtual waypoints manually after the global map was generated. The vehicle also renews global map data in each run to improve its running distance because it travels the same course repeatedly.

FAILURE MODES, FAILURE POINTS, AND RESOLUTIONS

- Failure: Orange2017 showed the tendency to not go straight forward in between white lines because the waypoints are not set straight ahead of the vehicle.

  Resolution: We set virtual waypoints located at the points that the vehicle would likely pass.

- Failure: We tried to make use of all maps generated in past runs to enlarge the global map. However, doing so ended up muddling the origin and the axes of the coordinates.

  Resolution: We decided to utilize only the map generated in the previous run to extend the running distance by repetition.

- Failure: The omnidirectional camera and circuit, especially the gyroscope, tend to heat up, and there was a possibility of thermal runaway and breakage.

  Resolution: We attached cooling fans to those components. Fan cases and covers were fabricated using a 3D printer.

- Failure: In the case of bad weather, the vehicle is not water proof.

  Resolution: For weatherproofing, we customized a bicycle rain poncho to cover the vehicle.

- Failure: Vehicle width is relatively short compared to its vehicle length, so it tips over easily.

  Resolution: We increased vehicle width to improve motion stability.

SIMULATIONS

In ROS, an open-source simulation environment called Gazebo is available. To test the decision-making capability of Orange2017, a virtual space with parameters similar to that of a real environment was used to understand the behavior of Orange2017. The simulation proved to be useful because testing is an inevitable step in understanding the cause of errors and improving the vehicle. The recorded data can be disproved in a real environment, thus we can test the vehicle in a virtual environment beforehand.

PERFORMANCE

This section discusses the performance of Orange2017.

Table 7. Performance of Orange2017

Measurement	Performance prediction	Performance result
Speed	5.4km/h (3.4mph)	5.3km/h (3.3mph)
Ramp climbing ability	19% incline	18% incline
Reaction time	0.19s	0.18s
Battery life	3h	2.5h
Obstacle detection distance	0-9m(0-30ft)	0-9m(0-30ft)
Waypoint navigation	± 0.09m(±0.29ft)	± 0.12m(±0.39ft)

CONCLUSION

In this paper, we presented the design and implementation of Orange2017 based on the D-case model, which was used to address the hardware and software problems of Orange2015, which was entered into the 23rd IGVC.

Based on the result of IGVC 2015, we developed a robust and reliable vehicle system by using ROS, a new 3D-LIDAR, and a new omnidirectional camera. In addition, we changed the vehicle dimension ratio to improve vehicle motion stability, and developed a custom vehicle controller module to improve vehicle electronic design stability. These capabilities are expected to improve safety, dependability, and durability of the mobile vehicle. With these new functionalities, we expect Orange2017 will fare well in the IGVC this year.

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