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Autonomous Golf Cars for Public Trial of Mobility-on-Demand Service

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Abstract— **We detail the design of autonomous golf cars which were used in public trials in Singapore's Chinese and Japanese Gardens, for the purpose of raising public awareness and gaining user acceptance of autonomous vehicles. The golf cars were designed to be robust, reliable, and safe, while operating under prolonged durations. Considerations that went in to the overall system design included the fact that any member of the public had to not only be able to easily use the system, but to also not have the option to use the system in an unintended manner. This paper details the hardware and software components of the golf cars with these considerations, and also how the booking system and mission planner facilitated users to book for a golf car from any of ten stations within the gardens. We show that the vehicles performed robustly throughout the prolonged operations with a small localization variance, and that users were very receptive from the user survey results.**

I. INTRODUCTION

Vehicle ownership is increasing rapidly. As of 2010, the number of vehicles in use in the world is estimated to be 1.015 billion [1], while the world population is estimated to be 6.916 billion [2]. This translates to one vehicle for every seven persons. Major cities around the world that experience rapid population growth are finding it difficult for their infrastructure to keep up. Mobility-on-Demand (MoD) transportations systems [3], such as car sharing or taxi services, can be used to address the "first and last mile" problem by complementing and encouraging the use of public transport. This will lead to reduced private vehicle ownership and greater transportation network connectivity, which in turn will result in reduced traffic congestion as well as reduced overall commuting time. One of the main challenges of a MoD system is in the rebalancing of the vehicles to ensure minimal waiting time for the customers at a sustainable cost. An optimal and real-time rebalancing policy that can operate under stochastic customer demand is presented in [4]. One means of rebalancing the vehicles in a MoD system is to utilise autonomous vehicles [5], [6].

Autonomous vehicles offer additional safety, increased productivity, greater accessibility, better road efficiency, and have a positive impact to the environment. While the merits to using autonomous vehicles are aplenty, allowing this transportation paradigm shift to materialise will require the concurrence of (a) technology maturity, (b) government support, and (c) public acceptance of autonomous vehicles.

For the purpose of raising public awareness of autonomous vehicles and gaining user acceptance of the technology, a public trial involving two autonomous golf cars was conducted at the Chinese and Japanese Gardens in Singapore over the course of two weeks [7]. Members of the public were invited to experience the autonomous vehicles first-hand and could select any of ten destinations within the gardens. Visitors to the gardens could call for a vehicle via a website as well as monitor the status and positions of all vehicles in the gardens in real-time.

This paper describes the system architecture and design of the two autonomous golf cars, which are of an improved design over their predecessor [5]. As the golf cars had to continuously operate for at least six continuous hours with members of the public, which include children and the elderly, riding in them, it was essential for the golf cars to be robust, reliable and safe.

II. RELATED WORKS

The focus of this paper is on automated road shuttles (e.g. golf cars, mini-buses). This type of vehicle typically operates at lower speeds in pedestrian environments and serves as a form of public transit. This section discusses two relevant topics. First, it describes trials and commercial operations of these vehicles that are underway. Second, it describes different approaches that have been taken for the various functionalities involved in autonomous navigation (e.g. localization, pedestrian detection).

There are several places where automated road shuttles are in commercial operations. Examples of such operations include Rivium Business Park, Masdar City, and Heathrow Airport [8], [9]. The common feature of these operations is

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that road vehicles are certified as a rail system meaning that vehicles operate in a segregated space [9]. This approach has been necessary because of the legal uncertainty around liability in the event of an accident involving an autonomous vehicle. To address this, governments around the world are reviewing and implementing new laws. Part of this process has involved extended public trials of automated shuttles the largest of which have been CityMobil and CityMobil2 [9].

In all of these activities there have been different approaches used to achieve autonomous navigation. While some fundamental differences exists (i.e. self-contained versus reliance on infrastructure), the different approaches vary primarily on their level of redundancy. In terms of localization, the following combinations have been used in conjunction with odometry: infrastructure magnets [8]; LIDAR only [10]; LIDAR and camera [11]; LIDAR, camera, and DGPS [12]. In terms of obstacle detection, the following combinations have been used in conjunction with LIDAR: LIDAR only [6]; ultrasonic [8], [13]; camera, radar, and infrared sensors [14].

III. HARDWARE OVERVIEW

The Yamaha YDREX3 electric golf car was used as the vehicle base platform and further retrofitted by our team to incorporate necessary actuation, sensing, computing, and power systems along with various additional features to enhance passengers' comfort and safety. Key elements of the retrofitted systems are highlighted in Fig. 1.

Fig. 1: Hardware overview, highlighting primary retrofit additions to a Yamaha YDREX3 golf car in order to enable autonomous capability.

A. Power System

It was initially intended for all retrofit electronics to be powered by the stock in-vehicle 48V 170Ah lead-acid battery, and all other required voltage levels were supplied by power regulators. However, it was found that the voltage level of the batteries would drop below the power regulator's minimum operating level when the golf car's motors were stressed, e.g., when climbing steep slopes, resulting in some of the equipment to shut-down. To address this, an auxiliary battery was added, consisting of 4 units of 12V 5.1Ah (60 to 90 Amp. maximum discharge) batteries, placed in series with an in-house voltage conditioner circuit (acts similarly to an uninterruptible power supply). The auxiliary battery only supplies current to the system when the main battery drops below 48V, and will recharge alongside the main battery pack whenever the stock vehicle battery charger is plugged in. All critical components (computers, sensors, motors, etc.) are protected from overcurrent using circuit breakers and fuses. Placing the auxiliary battery in parallel with the main battery allows the auxiliary battery to be conveniently charged together with the main battery with the golf car's default charger. The power system is illustrated in Fig. 2.

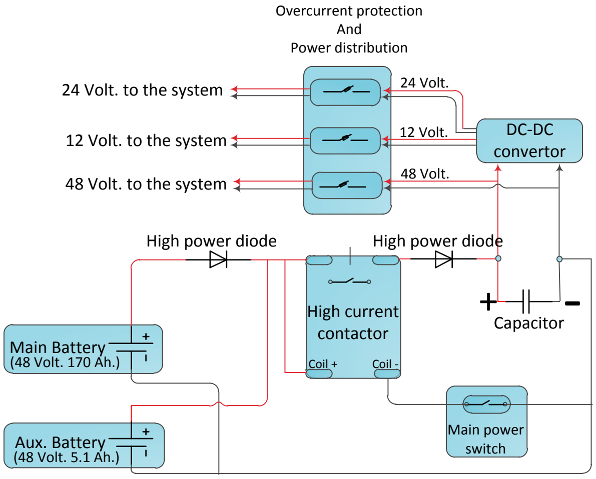


Fig. 2: Golf car power system

B. Actuation

To operate autonomously, the golf car's four primary controls must be accessible by computer commands: steering, throttle, braking, and transmission gear selection. To achieve this drive-by-wire functionality, two electric motors are used to control the vehicle's steering and braking. The throttle and gear shift are controlled via a microcontroller and relays to control signal inputs to the stock vehicle motor controller.

Steering motor sizing was determined by physically measuring the outputs of our team's human drivers on the golf car's steering column during normal operation. Steering speed was determined using a video recording, with the fastest achievable speed of 161 rpm (while the vehicle was in motion). A torque wrench was fixed over-top the steering column to measure maximum torque output, which was found to be 30 Nm (at static condition). Thus, a motor which could exceed 505 W power output was needed. These measurements are in close agreement with findings from similar human capability studies on full size cars [15]. The motor selected was a Deut Flexi 80 2 03 from Motor Power Company. This motor was mounted directly to the stock golf car's steering column sleeve, and transmitted power at a 14:1 gear ratio to the steering column (7:1 planetary gearbox and 2:1 spur gear). The mounting was designed and fabricated on NUS campus, with CAD design shown in Fig. 3.

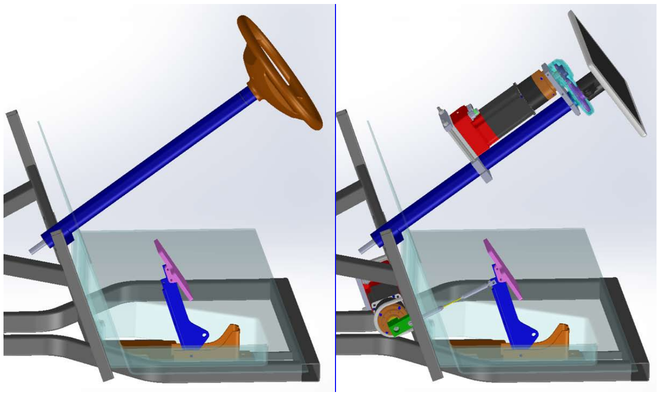


Fig. 3: Computer Aided Design (CAD) of steering and braking motor actuation. Stock configuration (left) and configuration retrofitted with motors for drive-by-wire controls (right). The steering wheel was removed and replaced with a touchscreen.

The braking motor was sized relative to the Society of Automotive Engineers (SAE) recommended practice maximum braking force requirement of 890 N exerted on the brake pedal, noting that this standard actually exceeds the physical capability of a large proportion of the population [16]. The same model Deut Flexi 80 2 03 from Motor Power Company was used in conjunction with a 7:1 planetary gearbox. The gearbox output shaft turns a lever arm and pulls a steel cable linked to the existing brake pedal (Fig. 3). Thus, when maximum braking force was applied, the only load on the motor was radial and very little current would be needed to maintain this state. This is ideal especially when considering this full-brake state to be used as a parking brake. Additionally, as the brake is actuated by a pull cable, a human driver would always be capable of pressing the brake pedal down further without impediment.

As the Yamaha YDREX3 golf car is powered by an electric motor, and the only gear selections are forward and reverse, both throttle and gear shift are controlled by interfacing a microcontroller with the stock golf car motor controller. Controlling these input signals via the microcontroller would in turn determine the input current to the driving motor. This was achieved by using the microcontroller to spoof electric signals (corresponding to the desired speed) to the motor controller which would otherwise come from the output of the stock potentiometer (linked to the throttle pedal). The same is done for the gear selection switch (high-low voltage signal). Relays are used to switch between the true sensor signals on the golf car and the microcontroller output signals to enable easy toggling between manual drive mode and autonomous mode. A STM32F3 microcontroller is used to publish signals to the stock motor controller and to read the states of the various user control buttons, e.g., manual mode, autonomous mode, emergency stop. The microcontroller, relays, buttons, and connections to the stock motor controller are all interfaced through a custom designed circuit board, with connection diagram shown in Fig. 4.

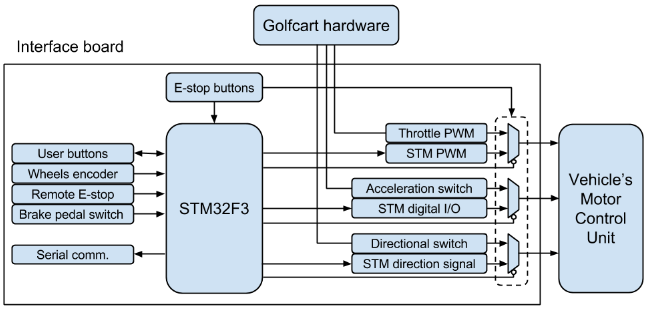


Fig. 4: Interface circuit board connection diagram

C. Sensors

Two non-contacting magnetic encoders are mounted to the rear axle of the golf car, one on each side of the drive shaft. A MicroStrain 3DM-GX3-25 Inertial Measurement Unit (IMU) is rigidly mounted to the chassis above the center of the rear axle to provide attitude and heading of the vehicle. The encoder and the IMU readings are combined to provide the vehicle's odometry information in 6 degrees-of-freedom.

Environmental sensing is achieved through several 2D LIDARs and a webcam. One SICK LMS 151 LIDAR is mounted at a tilted down angle from the front of the vehicle roof, where the data returned is fused with odometry readings to achieve localization by the methods described in [10]. A second SICK LMS 151 is mounted horizontally in the lower front of the vehicle for obstacle detection. Two SICK TiM551 LIDARs are mounted at the rear corners of the golf car to provide all around obstacle detection. The configuration is shown in a simulation environment for better visualization in Fig. 5. All sensors are rigidly mounted to the chassis using aluminum extrusion bars.

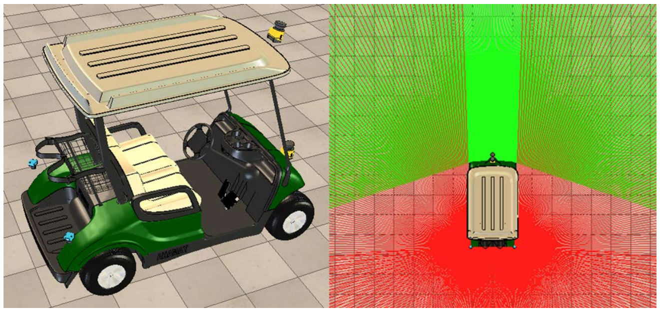


Fig. 5: Golf car LIDAR configuration (left), and top down view of the golf car with obstacle detection LIDAR scan lines shown as colored lines (right). SICK LMS 151 LIDARs shown in yellow, SICK TiM551 LIDARs shown in blue. Front LIDAR scan lines shown in green (50 m range), rear LIDAR scan lines shown in red (10 m range).

D. Computing

There are two computers installed in each of the golf cars. Both computers run Ubuntu 14.04 with Robot Operating System (ROS) [17] installed. The computers are built up using standard components of a desktop PC. Both computers are fitted with 4th generation Core i7 CPU, 16GB memory and 256GB SSD. The main computers CPU is installed with a liquid cooler to ensure that there is enough cooling effort to handle high environmental temperature, which is essential for prolonged operations in the gardens. It is also fitted with a discrete graphics card to handle additional GPU based processes and visualizations. The second computer is fitted with a 4TB hard disk and works as a dedicated black box that stores all the raw and processed data. For external communications, there is a 4G connection connected with the internal network and shared among the two computers. Also, a Cohda MK2 is fitted to each of the golf cars that provides vehicle to vehicle communication using 802.11 standard protocols. The computers are mounted to rear of the vehicle in a standard 5U size industrial rack (see Fig. 6).

Fig. 6: Computer rack with protective cover. Shown open (right) and closed (left).

IV. SOFTWARE OVERVIEW

The system architecture, which is common to both golf cars, comprises of four main modules: (1) perception, (2) planning, (3) control, and (4) external communication, as shown in Fig. 7.

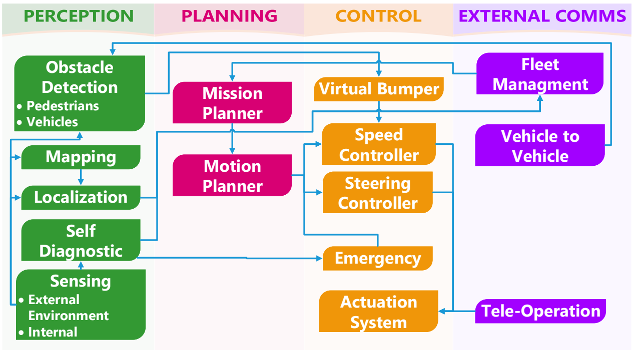


Fig. 7: System Architecture

A. Mapping and Localization

Preparation for the public trials started with data collection by driving the golf car manually around the gardens, covering all traversable regions in both directions. Then, a map is generated using methods described in [18]. In short, pose SLAM is used to build a consistent map of the garden environment. Localization is performed based on this built map. Synthetic LIDAR, a specific sensor model, is used to perform Adaptive Monte-Carlo Localization. The synthetic LIDAR makes use of the normals in a 3D rolling window as the main features that provide a unique fingerprint of the environment. Although it was originally designed for use in an urban environment that consist of concrete buildings and other man-made architectures, we found that the methodology adapts well in this natural environment. More details about the localization method can be found in [10].

B. Moving Object Detection

To ensure safe navigation of the autonomous vehicles, a moving object recognition algorithm is developed to detect and recognize other human agents in the shared environment [19]. The algorithm utilizes the spatial-temporal features of object clusters extracted from a planar LIDAR, and performs object recognition using a supervised learning method of Support Vector Machine (SVM). While this method is generic to any type of moving objects, moving pedestrian recognition is carried out for the vehicle moving in the pedestrian environment, which achieves both accurate and robust performance. Once moving pedestrians are recognized, their motion information (speed and direction) is calculated based on their centroid positions from consecutive measurements in the spatial-temporal clusters. The positions and the speeds of the recognized pedestrians are then passed on to the Dynamic Virtual Bumper module for vehicle speed control.

C. Dynamic Virtual Bumper

A Dynamic Virtual Bumper (DVB) is introduced to generate the advisory speed for the vehicle's safe navigation in the presence of both static and moving obstacles. The DVB is defined as a tube zone with its center line as the vehicles local path, with its width w_t and height h_t as linear functions to the vehicle's speed v_t at time t:

$$
\begin{aligned}
w_t &= w_0 + \alpha * v_t^2 \\
h_t &= h_0 + \beta * v_t^2
\end{aligned} \tag{1}
$$

where w_0 and h_0 are the static buffers, and α and β are the coefficients that the side lengths grow together with the vehicle speed, which reflect the bumper's dynamic nature. LIDARs are used to detect obstacles in the vicinity. When an obstacle o_i enters DVB_t, the vehicle will generate an advisory speed of the new desired DVB, whose boundary is marked by the position of the obstacle. Since the desired DVB will be smaller than the current one, the new calculated advisory speed will dictate the vehicle to slow down. The idea of DVB is illustrated in Fig. 8.

The autonomous golf car relies on the DVB to generate a safe advisory speed for vehicle navigation in the presence of both static and moving obstacles. We denote the set of obstacles as $O = O_{static} \cup O_{moving}$, which is comprised of the set of static objects, O_{static}, and the set of moving objects, O_{moving}. While the current LIDAR measurements

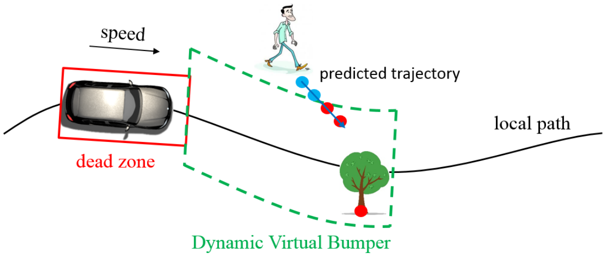
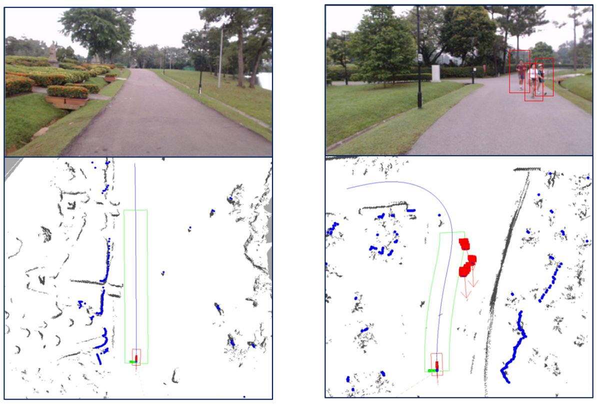


Fig. 8: An Illustration of the Dynamic Virtual Bumper.



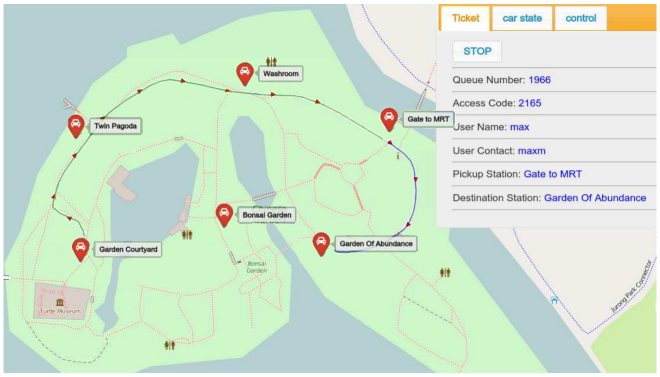
(a) Navigation without pedestrians (b) Navigation with pedestrians

Fig. 9: Vehicle navigation with/without pedestrians. The top row shows images from the onboard camera. The bottom row gives the plan view of the vehicle moving in the environment: the grey background represents the occupancy grid map; the blue dots are the laser points from the planar LIDAR; the green tube visualizes the DVB; red rectangles are the vehicles footprint; the red-green axes denote the vehicles base link. (a) clean scenario: vehicle speed 2.74 m/s, dynamic safety bumper grows larger as the speed increases; (b) pedestrian scenario: vehicle slowdown for recognized pedestrians, speed 1.96 m/s, dynamic safety bumper shrinks as the vehicle slows down for the pedestrians, and tries to keep the pedestrians outside of the bumper. The red blobs are the recognized moving pedestrians, with their moving direction visualized by the arrows

are directly used for static objects, O_{static} , the motion of moving objects, O_{moving}, have to be accounted for to guarantee safe navigation. Their trajectories are predicted for a certain time horizon, T. Both current and predicted positions are incorporated into $O_{moving} : O_{moving} = O_{current} \cup O_{predict}$. Fig. 9 illustrates how the DVB dynamically adjusts in the presence of pedestrians.

D. Booking System and Mission Planning

During the trials, members of the public could make a booking for a vehicle through our online booking system. A mission ticket is created in the format of [*Pick-up Station*, *Drop-off Station*], where *Pick-up Station* and *Drop-off Station* correspond to the passenger's pick-up location and passenger's destination respectively. The mission ticket is then sent to the central server which manages the database of all tickets in the mission pool. Given the large number of tickets in queue, the optimization of the mission schedule is performed by minimizing the vehicle travel distance and the passenger waiting time as a weighted function.



Queue Number: 1966
Access Code: 2165
User Name: max
User Contact: maxm
Pickup Station: Gate to MRT
Destination Station: Garden Of Abundance

Fig. 10: In-vehicle GUI. The vehicle is currently at *Garden Courtyard*. The green path represents the route $R_{veh;pick}$, and the blue path represents the route $R_{pick;drop}$, which the passenger intends to travel

Each autonomous golf car would fetch a mission ticket from the mission pool once its current mission is completed. After receiving the assigned mission, a route searching module would search two global traveling routes (or reference paths). The first route $R_{veh;pick}$ links the vehicle's current position to the *Pick-up Station*, and another one $R_{pick;drop}$ links the *Pick-up Station* to the *Drop-off Station*. A snapshot of the in-vehicle GUI displaying the route searching results is shown in Fig. 10. The route searching module performs a Dijkstra search over a directed graph of reference path segments reflecting the road network connectivity, as detailed in [20].

After assigning the reference paths for execution, the mission planner monitors the mission status. In our system, the mission statuses consist of *MissionWaiting*, *ApproachPickUp*, *ArrivePickUp*, *ApproachDestination*, *ArriveDestination* and *MissionInfeasible*.

E. Motion Planning and Steering Control

To upkeep the grass in the park, the golf cars were not permitted to drive outside of the paved walking paths, which were relatively narrow in many sections. Thus to meet this restriction the golf cars were programmed to follow predefined paths using a pure-pursuit steering controller. In the presence of a road blockage, e.g. by a large crowd of pedestrians, the vehicle would wait until the path is clear before proceeding. However, in other similar applications where driving on the grass were to be allowed, or if the main pathways were wider, it would be recommended to use a more sophisticated motion planner to replan paths and perhaps a different steering controller, as in a similar work involving these vehicles [20].

F. External Communication

The vehicles were capable of external communication over several networks including 3G/4G and Dedicated Short-Range Communications (DSRC). Aside from monitoring vehicle location and mission status, vehicle battery charge and operational status warnings were tracked and updates were also transmitted over 3G/4G to a central server to assist in fleet management.

It was necessary to use Vehicle to Vehicle (V2V) communication via a DSRC network for motion coordination of two way traffic along a single lane path. The Chinese Gardens and the Japanese Gardens are connected by one long single lane arched bridge. There is not enough clearance for two golf cars to pass each other on the bridge, nor is it possible for the vehicles to see the other side of the bridge to check for conflicts before entering onto the bridge path. Thus the vehicle(s) on one side of the bridge would be forced to wait until the bridge became clear of traffic traveling in the opposite direction. Details of the motion coordination method can be found in our previous work [21].

The vehicles were furthermore capable of teleoperation. Although this capability could allow oversight of large fleets of vehicles operating over wide deployment zones [22], it was unnecessary in this case with only two vehicles operating within a park, and thus the function was not used.

V. SYSTEM DESIGN FOR PRACTICAL USAGE

These autonomous vehicles were designed with the intended purpose of personal mobility application within Singapore's Chinese and Japanese Gardens for a pilot mobility-on-demand service. Special considerations were made to make these vehicles durable for prolonged usage in Singapore's climate and well suited for public usage for people from various demographics.

A. *Environmental Factors*

The vehicle was designed to be robust to various weather conditions encountered in Singapore while not requiring any additional infrastructure to be installed in the area. The primary environmental concerns in Singapore climate are high temperature, high humidity, dust, and rain. Thus it was necessary to have well enclosed electronics, yet provide sufficient cooling to the on-board computers. The computers are mounted inside an industrial rack with a liquid cooler and several fans. A hinged cover made from laser-cut acrylic was designed to protect the computer from rain (Fig. 6) while allowing easy access to the USB ports and computer power switch. The retrofit motors meet IP65 standard and all LIDAR sensors meet IP67 standard, ensuring dust and waterproof operation. Since the vehicle's environmental sensing is primarily reliant on LIDAR, vehicle operation is robust to variable lighting in night and day and unaffected by light to moderate rain.

B. *Human Factors*

During the public trial there were no demographic restrictions made to the users. The users were to be allowed to use the mobility-on-demand service without any driver or technical staff riding alongside them. Thus it had to be ensured that all user interfaces were intuitive and safe for all age groups.

1) Intuitive Interface: Bookings for trips can be made either at the vehicle itself using a touchscreen interface, or via mobile phone or web page. The user will be shown a location map and asked for pick-up and drop-off location, with an indication of estimated wait time prior to booking confirmation. The user is prompted on the touchscreen to confirm once they have boarded and are ready to depart. The passengers also have access to a separate custom button panel for some basic operations such as emergency stop or operation mode selection, with a choice of autonomous mode or manual mode (driven by game controller). An illuminated light on each button also serves as a visual cue to notify the user if the system has taken the command and responded to the user's request. Audio cues are given to the passengers (by weatherproof speakers underneath the golf car body panel) just before the golf car begins to drive off from the pick-up location, and again once they have arrived at their destination to let them know when it is safe to board or exit the vehicle. The steering wheel was physically removed, however the brake pedal was maintained such that the users can always press the brake pedal and temporarily "pause" the vehicle. The vehicle monitors whether this pedal has been pressed (via a stock switch) and if it is in autonomous mode while the brake pedal is pressed by the user, the throttle is temporarily set to zero such that the computer commands do not conflict with the user's intention.

2) Safety: The vehicle uses a dynamic virtual bumper to constantly adjust its velocity as detailed in section IV-C. Additionally, geofencing is used in the immediate area around predefined routes to ensure that the vehicle does not travel far from its intended path.

Since the steering motor drives the steering column of the vehicle in autonomous operation, this would also spin the steering wheel. This could pose as a safety hazard in the event that a passenger were to attempt to hold the steering wheel or overpower the steering motor. To prevent such potential injury, the steering wheel was removed from the golf car entirely (see Fig. 3). A joy-stick controller is used for manual mode.

Emergency stop switches are placed in easy to reach positions at the front panel for passenger access and also at the back of the vehicle for pedestrian access. While emergency buttons are commonly used in industrial setting, we recognized that many passengers may instinctively try to stop the vehicle using the brake pedal in response to emergency situations (as is natural in a manually driven car). To account for this, the vehicle monitors whether this pedal has been pressed (via a stock switch) and if it is in autonomous mode while the brake pedal is pressed by the user, the throttle is temporarily set to zero such that the computer commands do not conflict with the user's intention. A remote control also allows an outside observer to pause, resume and stop the golf car from a distance. This remote control was given to safety personnel during the trial who rode bicycles alongside the golf cars as a precautionary measure. The vehicle is also equipped with seat belts to ensure passengers remain seated in the event of any sudden stops.

3) Anti-vandalism: Several measures are put in place to mitigate the possibility of theft or misuse of the vehicles. The golf car steering wheel was physically removed and replaced with a touchscreen, thus driving the car manually would require the use of a game controller plugged into a running onboard computer. Computer access can be physically locked by closing the hinged-cover over top and using a lock in the hatch (Fig. 6), adding some physical protection. All push buttons are rated as vandal resistant, and are thereby not easily damaged. An additional power switch was installed in a hidden location beneath the vehicle as extra protection while the vehicle was in storage so as to disallow any throttle functionality. While the vehicles are in operation, sensor data including video footage could be recorded as well.

C. Scalability

While the trial only required preparation of two golf cars, the design is well suited for larger scale production as well. The conversion was kept as non-destructive as possible, where majority of the efforts consisted of disassembly and reassembly. The interface to the stock motor controller (to control throttle and gear selection), for example, requires only for the stock wiring harness to be unplugged from the stock motor controller and instead plugged into our microcontroller interfacing circuit such that this circuit acts as a "middle man" before the motor controller; the circuit will either pass through the true sensor signals from the golf car in manual mode, or pass signals generated from the microcontroller to the motor controller in autonomous mode. The computers are also secured in an standard industrial rack, which allows for many of the components to be preassembled and tested prior to installation. Also, although we developed the design based on the Yamaha YDREX3 golf car, the retrofit system can be adapted to other brands of golf cars or similar types of vehicles with minimal modifications.

VI. RESULTS

The trials were held at the Singapore's Chinese and Japanese Gardens - public accessible parks located at the western part of Singapore. The Mobility-on-Demand service operated from 8 AM to 2 PM for 6 days during the period from 23 October to 1 November 2014. Throughout the trials, temperature was in the range of 30.4 - 32.7 degrees Celsius with humidity ranging from 90% in the morning to 48% in the afternoon. Light rain was encountered during operation on the final day of the trails. Service was only halted briefly during one period of heavy rain for comfort of the passengers (seating area is not completely enclosed).

During the whole duration of the trial, the golf cars navigated reliably through all parts of the gardens. Fig. 11 shows the standard deviation plots of the localization system relative to the vehicles orientation. The plot is drawn with 0.5 m grid resolution. In each grid, the false color represents the average standard deviation value reported by the localization system. Localization variance remains well under 0.4 m with the exception on a section of the path near the center of the map. This is where the worst standard deviation values are reported. This section of the path consist of a 13-Arch bridge (approx. 45 m) crossing over Jurong Lake connecting Chinese and Japanese Garden. It is a particularly challenging environment due to lack of features and contains only repetitive geometric shapes similar to a long corridor. Longitudinally, the largest deviation is found to be 1.1 m and 0.8 m lateral deviation is reported. Overall, the average deviation on the longitudinal is 0.24 m ± 0.12 and 0.16 m ± 0.10 laterally. It can be seen that the deviation value is larger longitudinally. This is also true when comparing two plots visually where the lateral plot remains in the colder spectrum more than the longitudinal plot.

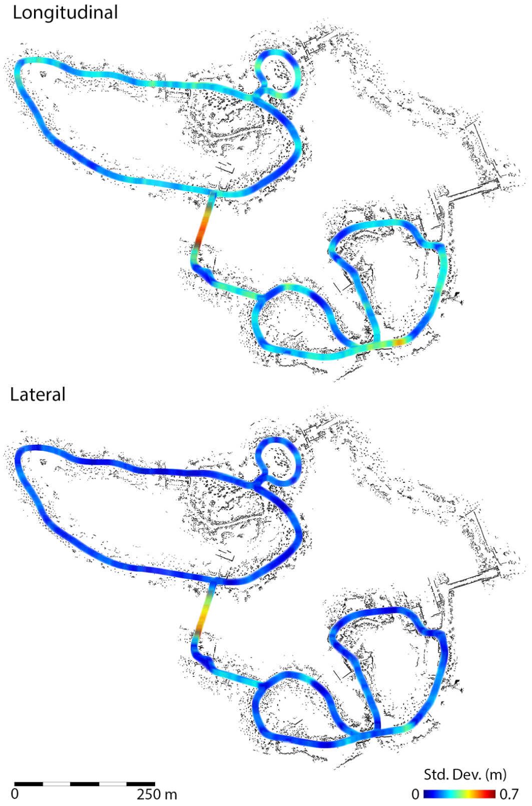


Fig. 11: Localization standard deviation results relative to the vehicles orientation (Top: longitudinal standard deviation, bottom: lateral standard deviation).

During the course of operations at the Chinese and Japanese gardens we estimate that SMART vehicles consumed approximately 100 kWh of power. The estimate was calculated based on the assumption that vehicles were charged from an empty state to 100% capacity for each of the six days of operations. The total combined distance traveled by the two golf cars was 351.6 km, as recorded by their odometry systems. The total number of trips was 220. A survey was conducted to gain user feedback of the trials. 223 survey forms were received and selected results are shown in Table I.

It was the first time for most visitors to sit on an autonomous vehicle. Users did not have a very deep un-

TABLE I: User Survey Results

How much do you know about self-driving vehicles?	2.5/5.0
How safe do you think self-driving vehicles are?	3.7/5.0
How would you rate your experience in terms of SAFETY?	4.4/5.0
How would you rate your experience in terms of COMFORT?	4.4/5.0
Would you ride on this self-driving golf car again in the future?	98% Yes
Would you be more likely to visit the gardens if the golf cars were a permanent feature?	95% Yes

derstanding about autonomous vehicles. This public trial affirmed our work and was very successful in raising public awareness about autonomous vehicle technology. Users gave an average rating of 4.4 (5 being the best) on their experience with regards to safety and comfort, higher than their perceived safety of autonomous vehicles (3.7/5.0). The first hand experience of users was critical in gaining user acceptance, as seen from their level of experienced safety and comfort. A video about the pilot with user feedback can be seen here: `http://youtu.be/aSm027Rzj9E`.

VII. CONCLUSIONS

In this paper, we describe the system architecture of our autonomous golf cars that were designed for public deployment in a pedestrian environment. Unlike typical experimental scenarios, the golf cars had to be designed to be safe, robust, and reliable, under prolonged operations while being subjected to the elements. The different implemented algorithms (e.g., mapping and localization, obstacle avoidance, Dynamic Virtual Bumper, booking system) have proven reliable over the prolonged operations. The purposes to raise public awareness about autonomous vehicle technology and to gain user acceptance were achieved as seen from the survey results.

In the future, we plan to work on a more efficient booking system. There is also need for a better predictor of the pedestrian's movements and for a mechanism in which the autonomous vehicle can relay its own intent to other pedestrians.

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