Cleaning up Smart Cities - Localization of Semi-Autonomous Floor Scrubber

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***Abstract*—The paper describes design and features of novel semi-autonomous floor scrubber add-on module, used for cleaning large indoor and outdoor tile/marbles spaces found in modern (smart) cities. Module is designed in such a manner that it can be easily added to and removed from scrubber machine and that additional sensors and capabilities can be introduced (modular design). In the paper localization capabilities of the machine in three sensor setups are presented and analyzed. Analysis is performed in terms of localization accuracy and reliability as well as associated advantages and disadvantages. Obtained results demonstrated that inclusion of UWB subsystem, despite its price and accuracy (± 20 cm in ideal, line of sight, conditions), yields more reliable and accurate results in open spaces (up to 25 times in position and 2 times in orientation) where performance of used Lidar might be sub-optimal.**

I. Introduction

Modern cities, regardless of their size, have number of buildings (shopping malls, offices, schools, universities, hospitals, etc.) and outdoor spaces (squares, shopping streets, etc.) that require constant care and cleaning. This is traditionally done during the day (although exceptions exist for open spaces) with specialized machinery and trained personnel. This can interfere with normal functioning of the space and takes up resources that could otherwise be better utilized. Labor shortage is also an important factor [1]. Thus, if this process could be automatized and performed during off-work hours improved user experience and safety as well as savings could be achieved. Additionally, if this could be managed in economically feasible manner using already available floor scrubbers and modular based approach (ensuring efficient and easy upgrades) it could be attractive to wide audience.

In recent years, due to reduction in size and cost of sensors and off the shelf embedded computers, as well as increase in their computational power, service robotics has grown significantly. According to ISO 8373- 2012 standard [1] a service robot is a robot that performs some task useful to humans (or other equipment) excluding industrial applications. Investments in robotics as a field grew about 240 million USD in 2015 and they account for about a third of all investments in HAX start-ups [2]. Other studies [3], [4] noted that service robots will reach a global market volume equivalent to industrial robots (which is estimated to be over 15 billion Euros) between 2020 and 2025. This has been additionally fueled by software developments like Willow Garage's Robotic Operating System (ROS) [5], which is becoming increasingly used by researchers and private companies alike.

A. Related work

Specialized autonomous industrial sized floor scrubbing robots already exist as complete and finished products[2] and in advanced development stage[3]. Unfortunately their price is usually much higher then regular industry size scrubbers. On smaller scale, Roomba is probably the best known example of the autonomous service robot [6]. It was firstly introduced in 2002 and up to February 2014 over 10 million units were sold. Recently, new model Roomba 980 was introduced, which uses a camera for vision Simultaneous Localization and Mapping (VSLAM) [4]. Other, similar, products also use localization for increased cleaning efficiency but using different hardware like Neato XV-11 from Neato Robotics [7]. Some more recent developments in the field of service robotics include Fetch and Freight robots from Fetch Robotics [8]. It is worth noting that both Fetch and Freight are based on ROS. The development of the robot pair (manipulator and moving base) is motivated by the fact that there are estimated $600,000$ unfilled jobs in the logistics industry, and that e-commerce is expanding industry with sails increasing by about 15% to around 300 billion USD in 2014. Similar product exist from other manufacturers like OTTO robot from Clearpath Robotics [9]. Another service robot that uses ROS for its operation is Relay from Savioke [2]. The robot is intended for hotels as room service delivery tool. It has been already implemented in several hotels like Crown Plaza Silicon Valley, San Jose, USA and Marriot, Los Angeles, USA. Other similar products are, Dispatch (open space delivery robot) from Distpatch robotics[5], FellowTwo (retail store assistant) from Fellow Robots[6], Adept robots (mutifunctional service robots and mobile base) from Adept Technology Inc.[7] and Care-O-bot 4 (multipurpose service

[1] http://acetool.commerce.gov/labor-costs

[2] http://www.intellibotrobotics.com/products/

[3] http://www.flobot.eu/

[4] http://spectrum.ieee.org/automaton/robotics/home-robots/irobot-brings-visual-mapping-and-navigation-to-the-roomba-980

[5] http://www.dispatchrobotics.com/

[6] http://fellowrobots.com/

[7] http://www.adept.com/products/mobile-robots

robot and robot bases) from Fraunhofer Institute Manufacturing Engineering and Automation[8].

Localization plays important role in (semi)autonomous service robots. In [10] a stigmergic approach was used in conjunction with RFID-based navigation maps in goal-directed navigation of full-scale robots like Turtlebot and Scitios G5. Robots navigated in $80m^2$ apartments which were a part of a larger residential area for senior citizens[9]. In [11] possibility of application of mobile robots to move materials around a hospital was examined. Semi-autonomous mobile robots were suggested as possible solution relaying on visual tags (ID based augmented reality markers and 2D barcodes) due to their ease of installation, low cost and constructional simplicity. Besides hospitals, robots can be used to provide care to elderly in their homes [12] or as means for a extended telepresence of medical professional [13]. Mobile robot navigation was also in focus in [14] for applications such as transportation, cleaning, search and rescue and surveillance. The work presents several approaches to efficiently estimate state of the robot while performing SLAM as well as estimate of the model of the environment (including highly complex and dynamic environments). Service robot navigation systems for similar applications in indoor environments [15] and in highly structured outdoor environments (like vineyards and orchards) [16] are being also developed.

Our aim was to produce add-on module that would transform standard scrubber to autonomous one and that could, in case of need, be easily moved to other machine or upgraded. The robot would still need human intervention for filling up water tank and cleaning agent and subsequent disposal of dirty water. For scrubber localization in known space we propose innovative application of UWB system (which is currently not widely used in robotics) and Lidar. The remainder of the paper presents proposed add-on module and its localization performance under three sensor setups. It also provides brief analysis and proposes future research directions.

II. Materials and methods

The add-on module consists of three main parts: mechanical construction, electronics including drive motor, sensors and controllers, and software. For testing purposes it was mounted on Hakomatic E 530 floor scrubber which measures 123 cm in length and 53 cm in width. The scubber weighs in (without the add-on module) around 200 kg and can travel with speeds up to 5 km/h. It has its own 24 V battery pack that powers scrubber brushes as well as vacuum extension that picks up excess water from the floor.

A. Mechanical construction (Motor Column)

Main part of the module is 4 mm thick steel construction in form of two columns, each placed on one side of a floor scrubber. Each column is a three level construction that holds the drive motor, drive wheel with wheel encoder, and power supply (12 V 25 Ah deep cycle battery) and is depicted in Figure 1. It is secured to the floor scrubber via two bolts, which are easy to undo in case of module removal. In order to achieve this, a metal beam was added to undercarriage of the floor scrubber (and is barely visible from outside/above). That was the only change made to original machine. The beam does not interfere with normal operation of scrubber in case a human operator takes over.

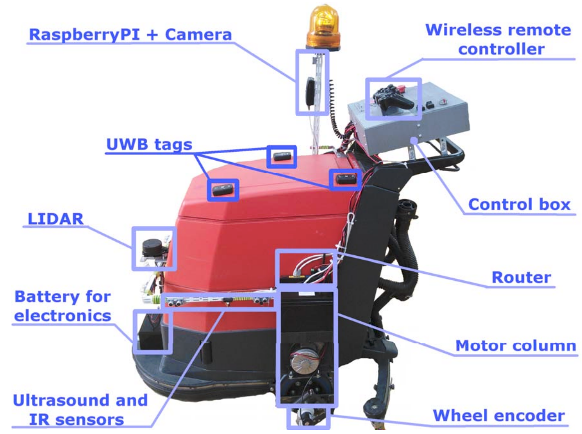

Figure 1. Overview of complete semi-autonomous system with highlighted individual components of add-on module.

Motor drive is connected via chain drive and gears to the drive wheel. In parallel with the main wheel, smaller encoder wheel is added along with gear system. In order to secure better friction, and to minimize sliding effect, encoder construction is additionally pressed to the floor by strong metal spring. The wheel is responsible for driving the wheel encoder and detecting robot/scrubber movement. This configuration allows for accurate tracking of robot movements and is robust against slips of the drive wheel (e.g. due to the wet floor).

B. Electronics

Majority of electronic components (except forward sensors and drive motor) are placed in single 3D printed case, which is mounted on the scrubber handles using existing wholes and screws. On top of the box is red mushroom type master switch that can be pressed in case of emergency, and which disables drive motor and its controller. Schematic diagram of developed electrical systems is shown in Figure 2. The main part of the module system is a Raspberry Pi 2 embedded computer. It uses Ubuntu 14.04 LTS and ROS (running *roscore* and sensor measurement nodes). Five components are connected to the embedded computer: Lidar, IMU unit, Arduino Due (for ultrasound and IR sensor data processing), motor driver (which drives the motors and communicates with wheel encoders), joystick wireless controller, and WiFi dongle (used for debugging). It should be noted that IMU, ultrasound and IR sensors were not used in the paper. Also, it is worth noting that rotating light column contains a second Raspberry Pi (running Apache server and connected to system's router) along with Pi Cam for real time video feedback. In this manner a teleoperation from distant location could be achieved.

[8]http://www.care-o-bot-4.de/

[9]The Robot-Era FP7 project: http://www.robot-era"

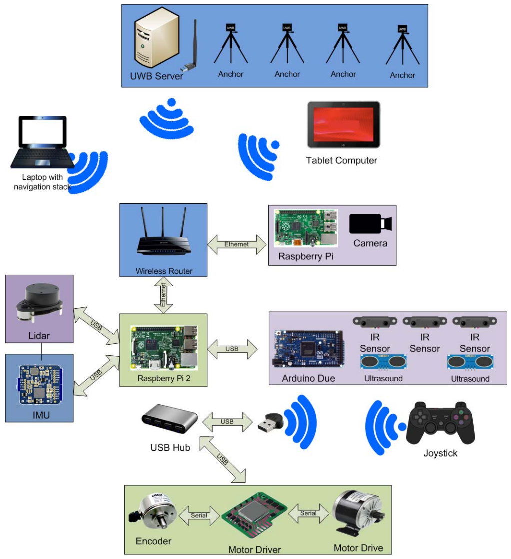

Figure 2. Electronic components block diagram.

Second important part of the system is a laptop computer with sufficient computational power (Intel i3 processor with 4GB of RAM running Ubuntu 14.04 LTS) which easily runs ROS Navigation stack as well as real time visualization of robot surrounding and actions. Since placing the laptop computer on the scrubber is impractical we opted for wireless network based design which is greatly facilitated by ROS architecture. This was done since preliminary testing demonstrated that RPi 2 is not powerful enough to do that in real time.

The key network component of proposed prototype is wireless router (Asus RT-N10E) attached to the scrubber to which Raspberry Pi 2 was connected via Ethernet cable. This in turn does introduce range issues for the scrubber (related to strength of WiFi signal). This configuration allows all key components to exchange information in real time, and offers flexibility in terms of possible future upgrades. It also allowed for easier integration of UWB measurement system which took place on separate computer. UWB system provides absolute position of battery powered tags, and is based on DecaWave DW1000 chip. It enables indoor and outdoor positioning accuracy to about 20 cm in ideal (line of sight) conditions. However UWB systems suffer from random jumps in location estimation due to different signal paths especially in non line of sight conditions, limited range (up to 100 m depending on space configuration) and need for synchronization which imposes certain requirements on available infrastructure and their connection. Note that three tags were placed on the scrubber for more accurate tracking of position and orientation of the device [17].

All electronics (except drive motor and its driver, and UWB tags) were powered by additional battery pack (12 V, 12 Ah) with three voltage stabilizers (5, 9 and 12 V). Table I contains information on makes and types of used electronics. Note that all components are off the shelf with exception of motor driver which was built in-house and has several unique features like custom wireless communication protocol, battery charging capabilities, interrupt based communication and data gathering from wheel encoders to reduce workload of Raspberry Pi 2.

Table I
MAKE AND TYPE OF USED ELECTRONIC COMPONENTS

Motor drive	MY1016Z2 250W
LIDAR	RoboPeak RPLIDAR 360
UWB Localization subsystem	Sewio RTLS system
Ultrasound	HS-SR04
IR	Sharp GP2Y0A41SK0F
IMU	UM7-LT
Wheel encoder	LPA3806-600BM-G5-24C
Main controller	Raspberry Pi 2 Model B
Auxiliary controller	Arduino Due

C. Software and Algorithms

Robot Operating System (ROS) was used as a basis for robot operation along with open source navigation and localization plugin in called ROS navigation Stack[10]. Navigation stack has readily available localization algorithms like Advanced Monte Carlo localization (AMCL) as well as navigation and obstacle avoidance algorithms.

ROS environment was chosen because of several reasons: 1.) open source platform, 2.) lots of already developed tools, 3.) existence of drivers for different sensors, 4.) the code structure is standardized, 5.) modular design, 6.) parallel performance of various applications - if one node goes down it will not cause other nodes to stop working and 7.) synchronization between running applications as long as they are under the same ROS master.

Additional ROS nodes (name given to ROS based programs) for collection and processing of sensor data were written. One node low-pass filtered UWB measurements to remove sudden jumps in robot position inherit to UWB systems (which we know is not possible due to dimensions and weight of the robot). It also removed a measurement bias observed with particular real-time location system (RTLS). Then it used algorithms from [17] to obtain more accurate estimation of position and orientation of the scrubber. Example of accuracy after the procedure is depicted in Figure 3. Gaussian like distribution can be seen in the figure with values ranging up to 15 cm which we take as accuracy of the system. Same Gaussian distribution was observed for each of three tags used in the setup.

Second ROS node was used to process data from wheel drives and output estimated position and orientation (i.e. for wheel odometry) [18]. Node containing AMCL localization was used for calculation of co-variance matrix and triggering of UWB+Lidar integration when variance thresholds was reached.

[10] http://wiki.ros.org/navigation

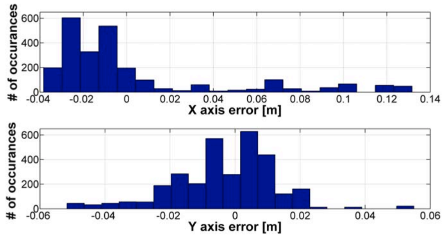

Figure 3. Example of histogram plots of UWB triangle accuracy.

III. Measurement setup

Accurate and reliable localization in known space is prerequisite for successful application of the module: the scrubber needs to know where it is so it knows where to go and what to clean. In order to test the performance of the proposed system, a realistic scenario was used: map of part of fourth floor of Faculty of electrical engineering, mechanical engineering and naval architecture, Split, Croatia was made (using SLAM and mapping capabilities of ROS navigation stack) as depicted in Figure 4. Please note in the some parts of the map (e.g. long hallways) there is some distortion which is introduced during SLAM mapping process. This however does not influence correct operation of the autonomous robot under Lidar localization since it can account for it. However, when working with UWB system this needs to be taken into consideration. Thus special care was given to mapping spaces within UWB system's range.

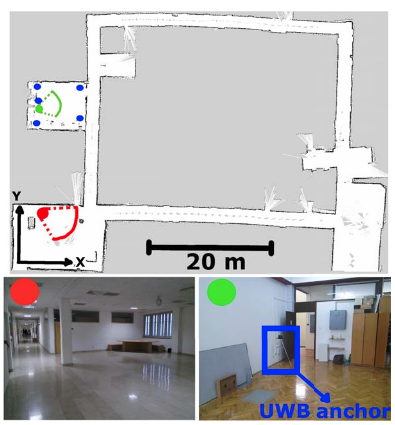

Figure 4. Part of measurement map and 3D view. Red and green dot and lines indicate position and direction of 3D view in relation to the map. Blue dots represent positions of UWB anchors.

Measurement procedure was as follows. Floor scrubber was in the known initial position and orientation. Human operator took control of the driving of the module (via wireless controller) and drove it around the map for about 15 minutes traveling in total around 200 m. This scenario is intended to mimic real world application where automatized floor scrubber would have to clean one floor of office type building. After completion of the lap operator parked the robot in the same position and orientation (which was previously marked on the floor). If localization measurements were ideal, robot should find itself in the same start pose on the map. Since ideal measurements are not possible, the difference between initial and final position and orientation is measured and reported (Table II). We note that knowing exact difference between robot's actual pose and pose in the map is not practical since it would require use of motion tracking hardware in all areas of measurement and it depends on SLAM performance.

For implementation of UWB and Lidar combination one room was equipped with 5 UWB anchors at known locations. When scrubber was in the range (which for particular setup was about 20 m from master anchor) of UWB system it's position was corrected for if predetermined conditions (number of Lidar scan points and/or AMCL co-variance estimates) were met. Position of UWB anchors can be seen in the upper and lower right parts of Figure 4.

IV. Results and discussion

A. Experiment 1 - Odometry and Lidar+AMCL positioning accuracy

The odometry and Lidar + AMCL measurements were taken at the same time so that their direct comparison is accurate and reliable. Obtained trajectories were recorded and are visualized in Figures 5 and 6. Please note that this represents robots belief in its current location and not actual location itself - thus through the wall trajectories are possible as in Figure 5. From the figures it is immediately evident that considerable drift is present in odometry measurements while Lidar + AMCL combination provides very accurate measurements.

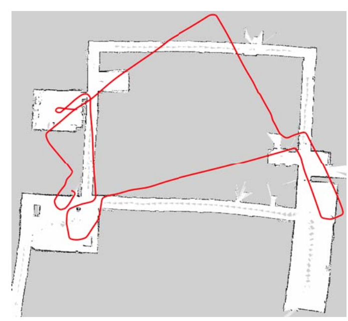

Figure 5. Motion trajectory calculated based on odometry measurements (*Odometry*).

Table II
Measured pose accuracy for all experimental conditions

Sensor setup	Position error [m]			Orientation error [deg]
	Total	X axis	Y axis	
Odometry	18.96	8.62	16.89	38.68
Lidar+AMCL	0.78	-0.77	-0.08	3.86
Lidar+AMCL+error	2.22	0.91	-2.03	-15.14
Lidar+AMCL+UWB	0.08	0.08	0.005	6.92

This is confirmed by the actual error in start-end pose as presented in Table II. This suggests that Lidar+AMCL is good choice as primary localization tool for the robot

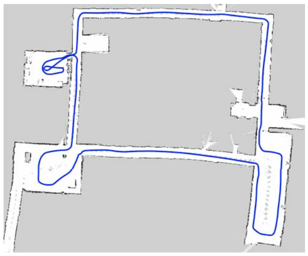

Figure 6. Motion trajectory based on Lidar measurements and AMCL algorithm (*Lidar + AMCL*).

module. It also provides robot with good obstacle avoidance capabilities. However, we recognize that during normal operation, automatized robot scrubber will operate in open spaces (e.g. warehouses and/or squares) where maximum rage of current Lidar (6 m) will not be adequate and robot might not get sufficient data for such an accurate localization. Then UWB based localization system might be of interest and its performance needs to be tested.

B. Experiment 2 - UWB correction of Lidar+AMCL positioning

In the experiment range and accuracy of UWB system compared to Lidar+AMCL combination was tested. Comparison of obtained results is depicted in Figure 7.

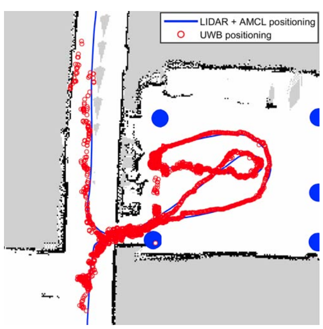

Figure 7. Comparison of motion trajectory based on Lidar+AMCL approach and UWB measurements.

From the figure it can be seen that UWB system localization follows closely that of Lidar based system. However due to price difference between UWB and Lidar system and required infrastructure interventions (i.e. installation of UWB anchors), Lidar based system is more sensible one for practical application. This is further reinforced by inspection of measurements in upper left corner of the Figure 7. Here UWB error is larger due to no-ideal measurement conditions (there is wall between UWB anchors and tags). Soon after, robot is out of range of UWB system. It should however be noted that such a limited range could also be due to WiFi limitations since UWB localization software was run on separate computer (due to high computational requirements) and forwarded to robot module via its router.

Nevertheless, UWB system could be useful in spaces with different topology (e.g. with more open spaces) where Lidar and consequently AMCL performance might be sub-optimal. UWB could then offer some usefull information in robot localization, despite its disadvantages. Since such spaces where not available at Faculty, we simulated it by putting paper cover over Lidar (as in Figure 8). Since Lidar firmware disregards readings of obstacles below 20 cm it would seem to Lidar that nothing is on that side (i.e. it is more than 6 m away). Robot floor scrubbers was again drove in the same floor by the same operator. Recorded trajectory can be seen in Figure 8

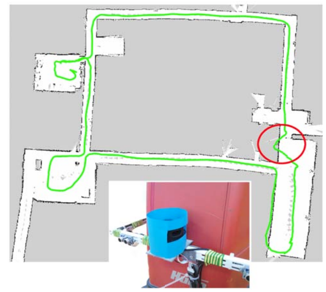

Figure 8. Lidar+AMCL trajectory under simulated fault conditions (*Lidar+AMCL+error*). Smaller inner figure depicts how Lidar measurements were introduced with error.Red circle marks area of highest AMCL uncertainty.

From the figure it can be seen that in some instances (e.g. red circle) robot "goes through the wall". These instances pertain to larger open spaces to the left of the robot (since due to paper cover robot cannot see to its right). Trajectory was also not as smooth as before. Robot localization in hallways was not affected as much, although AMCL variance (and thus particle cloud) was larger. How this uncertainty develops (when coming from a hallway to the room with UWB tags) can be seen in Figure 9. The further the robot goes in the open space (this was reasonably small room with $9x9$ m dimensions) uncertainty changes. In such situations when overall uncertainty goes over predefined threshold UWB localization measurement (with its co-variance) is injected in the AMCL algorithm as last estimate and it resumes from there. This is seen in Figure 9: green ellipse is position estimate after UWB correction while red ellipse closest to it is estimate before correction. Exact error in start-end pose for both cases (with and without UWB compensation) is presented in Table II.

It is also interesting to explore how AMCL uncertainty changed over time especially in larger spaces. This is depicted in Figure 10. From figure(s) it can be seen that there are several spikes in uncertainty (largest one both in X and in Y direction) corresponds to red circle depicted in Figure 8 i.e. in large spaces. Uncertainty is smaller in hallways but is still larger than in case when no paper cover was present. Figure(s) also illustrate that uncertainty in X direction (i.e. direction of motion) is much higher (up to 6 times) than in Y direction. Please note that, when talking about AMCL co-variances, X and Y directions are in relation to robot's coordinate frame and not the global coordinate frame as was the case before.

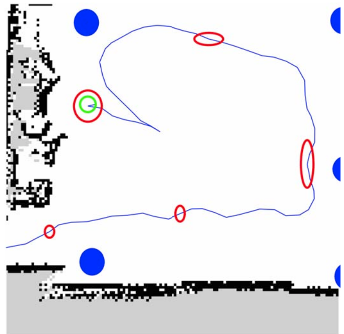

Figure 9. Lidar+AMCL trajectory under simulated fault conditions with UWB correction (*Lidar+AMCL+UWB*). Red ellipses represent AMCL uncertainty, green ellipse uncertainty after UWB correction and blue filled circle positions of UWB anchors.

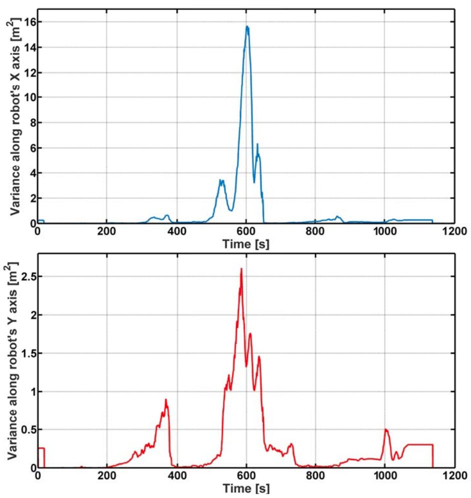

Figure 10. Variances for Lidar+AMCL trajectory under simulated fault conditions.

V. Conclusions

In the paper a novel add-on module which turns standard floor scrubber into a robot is presented. Its localization is very important since the whole operation depends on it (e.g. what and where to clean). Three sensor configurations were tested for accuracy. Testing showed that inclusion of UWB localization system (despite its higher price and need for intervention in the navigation space through positioning of UWB anchors) is beneficial and could improve Lidar+AMCL based localization accuracy and lower associated uncertainty in larger spaces where Lidar performance might be sub-optimal. We however do recognize that human intervention (through teleoperation interface) would be needed in some (rare) situations when robot's navigation algorithm fails.

Possible improvements of the system include upgrades in UWB based localization through coupling with odometry and or Inertial Measurement Unit (IMU) via Kalman filter, and UWB based SLAM mapping for more reliable maps. On the module side, inclusion of more powerful on-board computer to support navigation stack is required as well as inclusion of fully functional tele-operation subsystem which would enable off location human operator to take control in case automatic mode fails and robot does not know what to do.

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