

AVERT: An Autonomous Multi-Robot System for Vehicle Extraction and Transportation

Angelos Amanatiadis, Christopher Henschel, Bernd Birkicht, Benjamin Anel,
Konstantinos Charalampous, Ioannis Kostavelis, Richard May, and Antonios Gasteratos

Abstract—This paper presents a multi-robot system for autonomous vehicle extraction and transportation based on the “a-robot-for-a-wheel” concept. The developed prototype is able to extract vehicles from confined spaces with delicate handling, swiftly and in any direction. The novel lifting robots are capable of omnidirectional movement, thus they can under-ride the desired vehicle and dock to its wheels for a synchronized lifting and extraction. The overall developed system applies reasoning about available trajectory paths, wheel identification, local and undercarriage obstacle detection, in order to fully automate the process. The validity and efficiency of the AVERT robotic system is illustrated via experiments in an indoor parking lot, demonstrating successful autonomous navigation, docking, lifting and transportation of a conventional vehicle.

I. INTRODUCTION

Conventional car lifting and transportation systems are characterized by time-consuming solutions which demand human intervention in the loop. Their lifting and extraction configurations include towing, ropes and wheel lifter jacks. What is more, the current solutions are inadequate within confined spaces such as indoor parking lots, where the route clearance can often be performed only partially or even not at all, as access with conventional towing equipment cannot be guaranteed.

Automating the car lifting and transportation process will have a strong impact in several fields such as parking garages, emergency towing away services and explosive ordnance disposal by providing a faster and safer removal capability compared with the manual methods currently available.

In this paper we propose an autonomous multi-robot system for the remote lifting and transportation of vehicles with human intervention only in the decision making loop (which car to be moved and where to be transferred). The

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Angelos Amanatiadis, Konstantinos Charalampous, Ioannis Kostavelis, and Antonios Gasteratos are with School of Engineering, Democritus University of Thrace, 12 Vas. Sofias, GR-67100, Xanthi, Greece aamanat@ee.duth.gr, {[kchara](mailto:kchara@pme.duth.gr), [gstave](mailto:gstave@pme.duth.gr), [agaster](mailto:agaster@pme.duth.gr)}@pme.duth.gr

Christopher Henschel is with the Zurich University of Applied Sciences, Technikumstrasse 5, CH-8401, Winterthur, Switzerland hcls@zhaw.ch

Bernd Birkicht is with the BB-Ingenieure, Im Pfarracker 17/1, D-71723, Grossbottwar, Germany bernd.birkicht@bbingenieure.de

Benjamin Anel is with the Force Ware GmbH, Arbachtalstrasse 10, D-72800, Eningen, Germany benjamin.anel@forceware.de

Richard May is with the IDUS Consultancy Ltd, 10 Lime Close, RG41 4AW, Wokingham, United Kingdom richard.may@idusconsultancy.co.uk

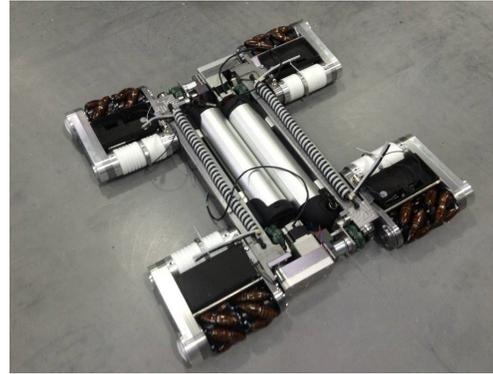


Fig. 1. The autonomous AVERT robot prototype.

novel developed robots, as shown in Fig. 1, are used to lift the selected vehicle from underneath by docking to its tires, and remain inside the vehicle’s footprint during lifting and extraction in order to maximize the opportunities for successful use when operating in confined spaces. The conceptual prototype was presented in [1], with this paper describing the detailed and final prototype with integrated autonomous functions.

II. RELATED WORK

A car transportation system able to support tasks such as parking, valet parking, and towing away services has been developed in Tohoku University [2], [3]. The robotic system was developed for parking purposes and consists of two robots being controlled by a decentralized algorithm for car transportation. Initially, the first robot grasps the two wheels on the left side of a four-wheeled car, whilst the second one grips the other two. Then, the two robots transport the car in coordination. The extracted trajectory is provided to the first robot, whilst the other one estimates its trajectory through the interaction force between them. An improved and downsized version of the first prototype was finalized at the same University [4], [5], based on the “a-robot-for-a-wheel” concept. The new version consists of four car transportation robots that can lift up and support a wheel of the car. Each robot slides two lift-bars under both sides of the wheel and then moves two racks on either side of a pinion to the opposite directions by rotating the pinion. Furthermore, a new decentralized control algorithm for coordinated car transportation was proposed, by using a leader-follower strategy and enabling the followers to estimate and reduce the motion errors.



Fig. 2. Deployment unit while releasing a Bogie pair.

III. ARCHITECTURE OF THE AVERT SYSTEM

The architecture of the AVERT robotic system was implied by the objectives and the routines that had to be accomplished through its deployment. The hardware arrangement and its characteristics, as well as the developed software architecture were designed so as to ensure the demanded level of accuracy, speed and safety. Specifically, the AVERT system is comprised of three subsystems, as shown in Fig. 2: (1) The Deployment Unit, (2) the Bogie Units and (3) the remote Command Center. Overall, the system is designed with supervisory remote monitoring and reversionary control, which can bypass the current processing and leave the system in a known safe state. Consequently, none of the current subsystem processing and software is deemed safety related. The final design structure recognizes the limited space and power available on the bogies and locates the most intensive processing activities on the deployment unit itself, with separate processors allocated to each of the functional subsystems.

Utilizing the aforementioned system components, a vehicle can be removed in a safe and effective manner by four sequential operation segments. The first stage is the *View* segment: the AVERT system remotely scans and rapidly maps the local area for vehicle recovery by capturing data on its surroundings and observing potential obstacles. The second mission segment is the *Plan* process, where after the initial view of the area, the system begins to plan the route for extraction based on the user vehicle selection. The analysis of the area, including obstacles and height restrictions are considered in order to calculate the most time efficient and safe trajectories. Subsequently, in the *Deploy* section, the bogies are deployed and tracked to the selected vehicle, docking onto the wheels and lifting the car fully off the ground. Finally, in the *Extract* phase, the bogies move the vehicle autonomously along the planned path avoiding objects at a slow speed.

A. Deployment Unit

The Deployment Unit (DU), is used to transport the bogie units to an overwatch position, close to the operating point. It

is designed to be both robust and cost-effective. The bogies are released by lowering the deployment unit's frame to the ground and letting them roll off. Apart from carrying the bogies, the unit is used to explore the operational scene and its environment during the *View* operational phase. The main data processing is held on it, hosting also the batteries and power units. On-board sensors include two SICK laser sensors, a Pan Tilt Unit (PTU) and a digital camera, which are mounted in certain heights through a mast. Particularly, as shown in Fig. 2, the 3D mapping sensor rig consisting of a vertically mounted SICK laser scanner and a co-located high resolution RGB camera are put at the top of the mast. The camera provides overview of the deployment procedure, as well as the texture on the constructed map. This mapping rig is mounted on a pan and tilt unit in order to provide a dense 360° 3D map of the environment. The SICK's angular resolution was set to 0.1667° and the PTU's angular velocity of the pan axis at $3^\circ/sec$. The 3D scan is produced by performing a 360° scan sweep. This assembly provides the autoscans function for the survey and mapping. At the bottom of the mast an identical SICK laser scanner is attached, which is responsible for the tracking of the bogies. This is mounted on a lift and tilt unit to allow the adjustment to the level and attitude of the bogies on sloping ground.

B. Bogies

The bogie subsystem including the respective sensors and actuators, provides the mobile docking and vehicle lifting mechanism for each of the four wheels of the vehicle. It also hosts the intercommunication between the sensors and actuators on each platform; and the processing of the control and trajectory information from the remote command center. This enables the platforms to operate as a coordinated group of robots in synchronism when lifting and extracting the subject vehicle. The bogie subsystem hardware comprises four bogie platform units with sensors, actuators, drive motors and batteries together with local processing and local data network communications unit. In addition, it includes their respective local data communications node, which is connected with the lower SICK laser sensor of the deployment unit for their tracking.

During the overall mission of the AVERT system the bogies can be appeared in two different states: (1) joined into two pairs, which is the case where the bogies are traveling in order to reach the Form Up Point (FUP) near to the selected vehicle, (2) split into four units, which is the case where the bogies deploy in order to dock, lift and extract the vehicle.

Autonomous control is also performed when under-riding the vehicles, moving into place from any approach direction to locate the vehicle's pick up points. Their design focuses exclusively on urban environments, thus they do not offer any outdoor capabilities like operating on soft surfaces, grass or uneven terrains. They are designed to cope with various existing car park floor types of typical restrictions and environmental conditions that allows a high sophisticated and accurate drive system design.

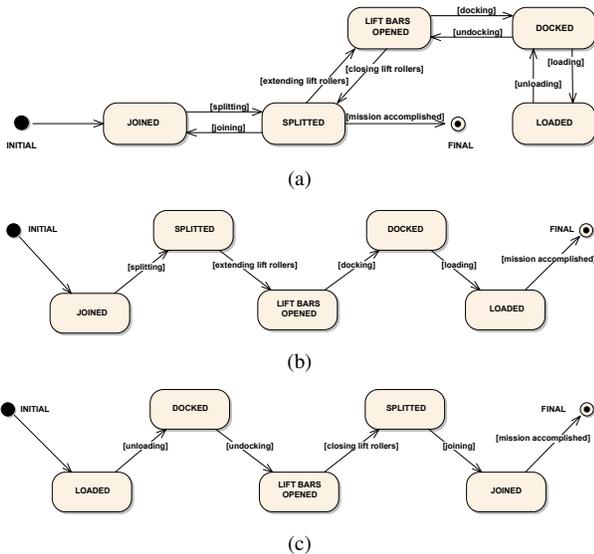


Fig. 3. Bogie states and sequences: a) basic bogie states, b) deployment and docking state sequence, c) vehicle lifting and extraction state sequence.

After being positioned underneath the target vehicle, the bogie design offers a commanded split of the bogie in two sections, enabling both bogie sections to manoeuvre independently, dock at the vehicle’s opposite wheels of an axle and lift them off the ground by compressing progressively two rollers against the tire, similar to commercially available car movers.

To prepare the Bogie control implementation a state chart of basic bogie states was built. Every bogie state requires specific control and therefore a different implementation. Figure 3(a), shows the state chart with all possible states and transitions. The various states were implemented as a state machine within the respective software component. Two sequences of bogie states are displayed in Fig. 3(b) and Fig. 3(c). After bogie deployment from the DU the bogies will be driven to a specific position in a “JOINED” state, be splitted into two bogies in a “SPLITTED” state, be driven to an appropriate position to extend the lift rollers during the “LIFT BARS OPENED” state, dock to the wheel while at “DOCKED” state and load the vehicle to remove it during “LOADED” state. The second sequence shows the roll-back to get back to initial state of first sequence, from “LOADED” state to “JOINED” state. The states presented in the diagrams can be changed using the given transitions. It is possible to perform state transitions in a loop if necessary. The state machine, which was implemented based on the state chart, allowed the development team to limit and simplify processing flows in the overall architecture.

C. Command Center

Since AVERT is designed to operate beyond line of sight it is important that the proposed solution should be designed to allow users to maintain awareness of the current and planned operations by the AVERT system and to provide the means for users to be able to assess when user intervention

is needed, allowing timely and effective user override to be actioned. Hence, a Graphical User Interface (GUI) has been designed to provide the users all the necessary information during the deployment and operation of the system. Additionally, the user should have the advantage to interfere with the system in the different steps of operation and start, stop or reset any process.

The entire system has been integrated into the implemented graphical user interface as a toolkit that allows the user to interact with the system and to execute the subordinate routines on demand. Due to the fact that the entire software architecture of the AVERT system is coordinated by the Robot Operating System (ROS), the developed GUI has been built on this framework. Therefore, the AVERT GUI was developed based on ROS, utilizing the Qt framework, which is a system that allows users to interact with and examine the ROS environment in a visual manner.

IV. BOGIE ROBOT MECHANICAL DESIGN

The typical gross vehicle weight of passenger cars and light vans is around 2.5 tons and the upper limit by law is 3.5 tons. The bogie systems are considered to provide the capability of lifting and moving vehicles with weights in excess of these figures according to the actual operational deployment. When displacing a lifted vehicle, the bogie’s totally installed driving power is sufficient to move the hooked mass according to the calculated moving parameters. A prerequisite for omnidirectional movement is that the driving power should split within the bogie system to all bogies, forcing them to have separate main drives for each bogie section. The bogie sections operate as a swarm, so power storage is split as well. The main drive system, therefore, is the battery supply based set of distributed electrical drives.

The omnidirectional movement design [6] permits the coordinated AVERT bogie units to manoeuvre the vehicle in any direction (literally the vehicle can be moved sideways or diagonally on the bogies, once the tires have been lifted off the ground). When required to pick up cars parked narrowly to walls, pillars or other cars, the bogie system has to operate within a confined space. The estimated distances between surrounding obstacles and the vehicle to be repositioned are unpredictable, but unobstructed vehicle accessibility is mostly possible from below. Under-riding a vehicle introduces several constraints. Mainly the chassis clearance limits an under-ride type bogie system’s maximum height. A typical ground clearance for private cars is 160mm (within Germany and Austria the minimum ground clearance is not limited but recommended at 110mm). The access to a car from beneath is limited by the track width, when this happens either by front or rear side, and the wheel base, when the access occurs sideways. Due to the fact that track width is always smaller than the wheel base, the vehicle’s track width constitutes the limiting measure for the bogie system’s maximum width.

The mechanical design of the bogies has required considerable research and design effort to enable the effective housing of the mechanical, electrical, power storage, sensor

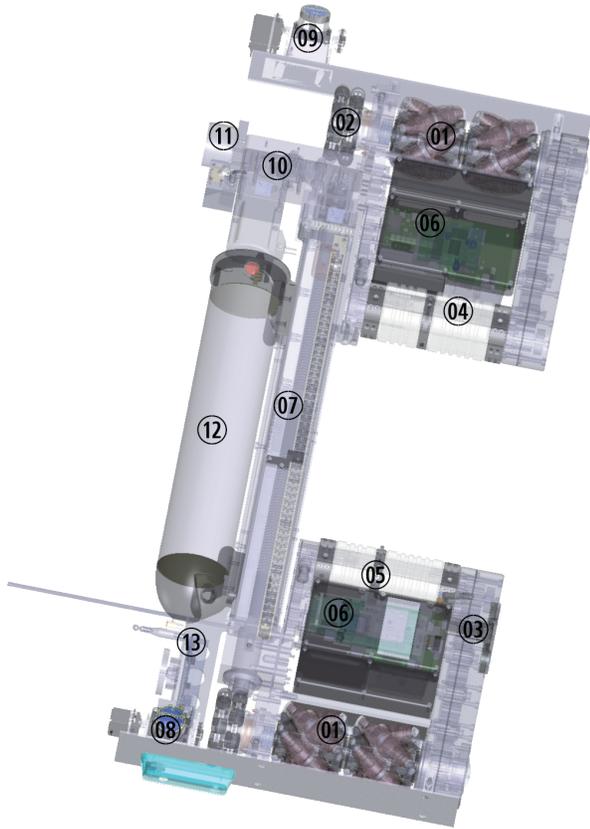


Fig. 4. Description of the split Bogie components: (1) Double load bearing Mecanum wheels, (2) braked omniwheel, (3) side camera and light, (4) lifting rollers, (5) tire docked sensor, (6) electronics box, (7) lifting unit, (8) docking and joining laser sensor, (9) forward obstacle laser sensor, (10) lift motors and gears, (11) joining/splitting magnetic catch, (12) removable battery unit, (13) joining location peg.

and communications components whilst maintaining the mobility and lifting requirements for the subject vehicle. Figure 4, shows the bogie design and features based on the outcome of the research tasks and prototype model trials. In addition to the labeled features, the bogie drive servomotors and their integrated controllers are located under the electronics boxes and they drive the Mecanum wheels through a drivetrain located in the gearcase on the side of each drive unit.

The drive motors are the integrated controller Lexium servo motors. The drive motor assembly is fitted with hold-off safety brakes which activate on loss of electrical current. These brakes are designed to be used in conjunction with the safety stop features of the drive motors on a controlled shut-down and when emergency stop is activated. Concerning the power source, a rechargeable lithium electric bicycle battery pack using LiFePO₄ chemistry has been selected. This represents an off-the-shelf solution with the lithium iron phosphate battery having one important advantage over other lithium-ion chemistries in thermal and chemical stability, which improves battery safety, yet it potentially carries about 14% less charge than Li-ion ones. Moreover, the Mecanum wheels have been specially engineered to achieve the desired load capacity following detailed load testing experiments and

stress modeling. The double wheel format is essential in order to meet the key load requirement and remain within the underide height. The omniwheel hub is also remote braking capable. The simple remote brake on/off approach was selected to leave the control electronics as simple and cost-effective as possible. The lift stepper motor is a two phase unit with external controller. The electronics units are housed in specially designed 3D-print manufactured enclosures, which are located above the drive motors and include the wiring vault for the drive motor connections and control signals carried over Ethernet to the integrated controller.

V. SOFTWARE COMPONENTS

The running software components are tightly coupled with the mission segments of AVERT. In the *View* phase 3D mapping and point cloud registration is performed in order to provide the area perception and calculate the bogies path trajectories of the *Plan* segment. During *Deploy* phase, the bogie tracking and swarm control is active along with possible re-routing due to new local obstacles detected by the bogie on-board sensors. Car docking and extraction is performed in the *Extract* section, where also the wheel detection has been carried out. Car unloading and bogie joining defines the successful mission.

A. View

For the 3D mapping, the sensor mast of the DU is utilized. A SCHUNK PW-70 servo-electric rotary pan-tilt actuator was chosen since it can accurately handle the load of the laser sensor, the mounting frame and the digital camera. The rotation angle for the pan axis was set 360°, while the maximum acceleration and angular velocity are 1440°/sec² and 360°/sec, respectively. Regarding the point cloud formation, the SICK LMS500 PRO 2D laser scanner was configured for vertical scanning. In more detail, the field of view is 190°, the angular resolution varies within the interval [0.1667° – 1°], the scanning frequency alters in the [25 – 100] Hz interval, while the scanning range is up to 80 m. According to manufacturer's specifications the standard deviation of the measurements is of 0.01 m. SICK's angular resolution was set to 0.1667° and PTU's angular velocity of the pan axis at 3°/sec. The 3D scan is produced by performing a 360° scan sweep.

Since a single scan sweep in a typical indoor parking lot will introduce various blind spots, multiple scans can be performed in different locations, with two scans being the best trade-off between scan coverage and required time. The point cloud registration is accomplished into two distinct steps based on a previous work by the authors [7]. First, a rough estimation of the transformation matrix is given using the Fast Point Feature Histograms (FPFH) features [8] followed by the Iterative Closest Point (ICP) algorithm [9] as a refinement step. FPFH are multi-dimensional features describing the geometry of a point belonging to a 3D point cloud. This feature derivation method is an expansion of PFH [10], which allows the on-line calculation of those

features, while it retains the discriminative capabilities of PFH, making it suitable for on-line applications.

Let us assume that the DU acquires two specific point clouds at t and $t+1$, respectively, such as ${}^t\mathbf{P}'$ and ${}^{t+1}\mathbf{P}'$. The DU's specific motion is described with a rotation ${}^t_{t+1}R$ and translation matrix ${}^t_{t+1}T$ and can be estimated by calculating the transformation among the FPFH correspondences resulted from the two point clouds as ${}^tP_{FPFH} = {}^t_{t+1}R \cdot {}^{t+1}P_{FPFH} + {}^t_{t+1}T$. The required rigid body transformation typically should conform with a sum of quadratic differences minimization criterion, resulting to a Singular Value Decomposition (SVD) optimization problem. By applying the motion transformation on the respective 3D point clouds we obtain a rough alignment and, as a result, the 3D map retains erroneous registrations. It is worth mentioning that for this rough alignment an initialization step takes place regarding the orientation of the robot by exploiting the orientation tracker device. Hence, the initially transformed point clouds are considered for the correction of the motion estimation. The most commonly used algorithm to fine register the 3D point clouds is the ICP one.

However, the novelty of the AVERT software algorithm is that the proposed ICP algorithm considers only the points that belong to specific geometric surfaces in consecutive time instances. The successive point clouds share great amount of spatial proximity, due to the fact that a coarse alignment occurred during the motion estimation procedure. The benefit from this procedure is twofold: firstly we avoid multiple iterations restricting the rigid body transformation search by one order of magnitude in calculation time and, secondly, we increase the likelihood to achieve an accurate solution. These advantages are feasible due to the fact that the considered points are contained in two successively observed scenes. Concerning the two successive 3D point clouds ${}^t\mathbf{P}'$ and ${}^{t+1}\mathbf{P}'$, we utilize a point-to-plane ICP algorithm [11], which seeks for a transformation K , that registers the two point clouds.

The output of the point-to-plane ICP algorithm is a transformation $K = [{}^t_{t+1}R_{ICP}, {}^t_{t+1}T_{ICP}]$ that aligns the two successive point clouds. The transformation K is combined with the initial estimation, as resulted from the FPFH registration and a refined estimation of the robot's pose is obtained, i.e. ${}^t_{t+1}R_{ref} = {}^t_{t+1}R \cdot {}^t_{t+1}R_{ICP}$ and ${}^t_{t+1}T_{ref} = {}^t_{t+1}T + {}^t_{t+1}T_{ICP}$. The calculated ${}^t_{t+1}R_{ref}$ and ${}^t_{t+1}T_{ref}$ are then introduced in the accurate registration of the successive 3D point clouds. This procedure is performed separately in each time step and, hence, the 3D map of the explored area is constructed incrementally.

B. Plan

The floor map enriched with the detected obstacles is provided as an input to a D* Lite method. The latter treats the problem as a graph-traversal one. D* Lite is a fast path planning and re-planning algorithm suitable for goal-directed robot navigation in partial known or unknown terrain. D* Lite constitutes an extension of Lifelong Planning A* (LPA*) [12], and one of its most significant additions is the variation where the target position changes dynamically during the re-

planning phases. Due to the fact that D* Lite expands LPA*, it also acquires the entire set of attributes that LPA* entails and its expansion capabilities as well. Compared to other methodologies, such as the well known D* [13], or CAO [14], D* Lite is simpler, can be rigorously analyzed, can be extended in various aspects and its efficiency is at least equal to D*. Regarding the simplicity, D* Lite utilizes a single tie-breaking rule for the comparison of the priorities, making their maintenance an easy task.

C. Deploy

The bogies operation comprises functionalities to execute a path planning algorithm; detect and report obstacles that the AVERT's perception system was unable to include, as well as to re-plan in such cases. Moreover, once the vehicle of interest is docked, the bogies are in place to operate as a swarm, retaining the aforementioned capabilities.

The bogie tracking is realized using laser scanning technology. The SICK LMS511 laser ranger, which is mounted at the bottom of the deployment unit, scans the environment at ground level, not higher of the bogie height. The tracking is based on two elements: the bogie shape dimensions and the reflectivity of its sides. To differentiate between the bogie sides and subsequently to detect a certain rotation of the bogie, retro-reflective foil is placed on two certain sides of the bogie. The chosen foil causes highest remission values of the laser beams which are measured by the laser scanner.

The bogie tracking process is elaborated in the following steps. Firstly, a conversion from laser raw data (polar coordinates, angle and distance) to Cartesian coordinate system is performed. A background subtraction is then applied in order to extract the points constituting the bogie profile. Line detection using Hough transformation of the extracted edges of the bogies allows the estimation of the bogie's orientation. Additionally, this step is used for outlier rejection of non-relevant points located too far from the extracted lines. The bogie's center point is calculated based on the extracted bogie edges and their associated points. The identification of bogie sides is achieved by comparing the mean remission value of the different sides. An optimization of center point and orientation using the Newton-Raphson algorithm follows along with a plausibility check for bogie pose position and orientation.

Controlling the four AVERT bogies in a common frame is necessary and starts on the moment that all four bogies are docked to the vehicle to be extracted. A basic requirement for the swarm control is the knowledge of each split bogie's pose. Recognizing the bogie poses, the width and length of the swarm as well as the orientation of the bogies to each other can be derived. The chosen strategy is to rotate the entire car close to its center of geometry until the car front faces the next trajectory point and then drive forward towards this point. Following this approach, the bogie on-board laser rangers can also scan adequately for local obstacles. Furthermore, the whole moving system is more robust when driving over obstacles, since the Mecanum wheels can overcome obstacles more efficiently when in forward direction. The

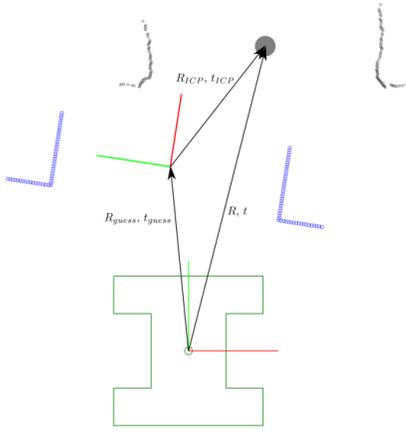


Fig. 5. Visualization of the tracking process: the estimate of the model is refined using the ICP algorithm to find the actual transformations R and t , which are then used as approximation for the next iteration.

implemented algorithm allows also vehicle rotation with the rotation center outside of the vehicle's footprint. The rotation of a bogie around a rotation point $C(C_x, C_y)$ is calculated in the following steps: (1) Define bogie position from rotation center perspective, $(Pos_{Bogie} - Pos_{RotCenter})$, (2) Rotate around angle α , $Pos_{Bogie} \times R$, where $R = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$, and (3) Describe bogie position in original coordinate system $(Pos_{Bogie} + Pos_{RotCenter})$.

The obstacle detection algorithm is based on the computation of height differences between two or more consecutive measurement time steps. The laser scanner is mounted to the bogie front side with a certain tilt angle α . Based on the current height h of the light reception coordinates O , the interior angle β and the slope distance s measured by the laser ranger, we use the equation $h = \cos\beta \times s$, for comparing the expected height h_e , which is known by the mechanical construction, to the real height h_r derived from the current slope distance measurement. The angle β is set as the constant interior angle of the triangle. Following this relation a height difference is given by $\Delta h = h_e - h_r$, where $h_r = \cos\beta \times s_r$, with s_r , the measured slope distance. Using the given formulas, the height differences due to obstacle presence can be easily derived from the measured slope distance. The defined tilt angle of the system is 40° and the height h_e of the ranger origin which is the light reception vertical coordinate of point O is 90 mm.

After the obstacles are detected, they are compared with the already acquired map and newly detected ones are appended on the map. As a result, this update triggers a re-planning process, where the D* Lite path planning is updated using the current position as a starting point of the bogies while the goal remains the same.

D. Extract

The *Extract* part of AVERT software deals with the wheel detection and docking, the extraction and unloading of the vehicle and finally the rejoining of the bogies. The wheel tracking algorithm is designed to autonomously steer the

bogie between the front and rear wheels of a parked car. This is achieved by analyzing the 2D scan data from the Hokuyo laser sensor mounted on the front of the bogie and by issuing driving commands in order to reach the center of the axles. After an initial detection of the left and right rear wheel, the algorithm starts continuously to track the rear axle by fitting an axle model of two L-shaped objects with the lower part of the L pointing outward to the wheel data points by using once again the ICP algorithm.

This procedure gives an incremental rotation R_{ICP} and translation t_{ICP} from the initial estimated position to the actual position of the scanner data. By repeating this process with updated laser scanner data, the algorithm continuously tracks the position of the rear axle. The overall process is described in the following steps: (1) Range data segmentation, (2) Setting of axle model points to estimated position, (3) Selection of segments within search range of estimated wheel positions; use of these segments for refinement of the axle position using ICP algorithm for R_{ICP} and t_{ICP} calculation [15], as visualized in Fig. 5, (4) Validation of the transformation by checking distance and angular change to previous transformation. If bogies are also in the line of sight of the lower SICK laser scanner, the relative motion between two successive bogie positions given by the bogie tracking is used for additional validation, and (5) Increment of transform parameters and use of transformation parameters as estimate for next iteration.

For the docking and lifting procedure tracking of the wheels with an additional Hokuyo laser scanner is required in order to control the movement. The position of the sensor is approximately on the virtually extended axis of the Mecanum wheels. This position provides a scanning angle α greater than 90° , since angles around 90° may cause bad reflections on the rubber of the tire. For the docking procedure, an iterative moving process has been implemented in three states: (1) Center the wheel gripper on the bogie to the wheel, (2) Minimize the angle between the bogie and the wheel, and (3) Sideways movement towards the wheel.

Finally, for the car unloading, all four lifting units expand synchronously until they are fully expanded. The current bogie joining process requires a position accuracy of less than $\pm 20mm$, which was very challenging. The extra Hokuyo ranger is used to perform this procedure in a controlled manner. As mentioned, the usage of the Hokuyo for joining requires line of sight with its partner split bogie (height of measurement plane).

VI. RESULTS

Each AVERT subsystem was evaluated and tested firstly independently, selecting when possible, the worst case scenarios in terms of environmental conditions, loading values and obstacles. The full-scale AVERT system was tested and evaluated in real conditions in an indoor parking lot.

The indoor constrained environment (walls, pillars and ceiling) enabled the accurate and particularly fast execution of the individual subroutines of 3D mapping and registration. In more detail, the scanning process exhibited a standard

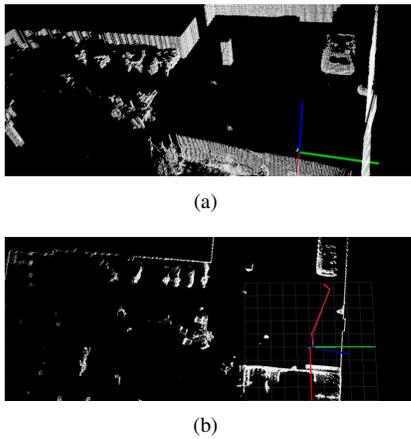


Fig. 6. The View mode of the AVERT system: a) The derived indoor map, b) the FUP extracted trajectory.

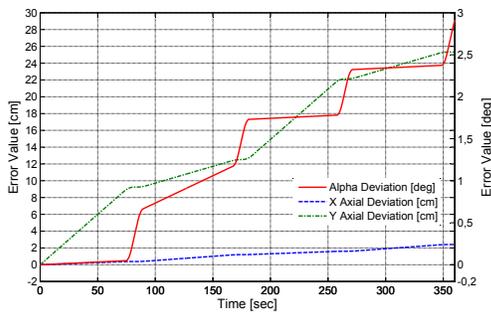


Fig. 7. Positional and angular error during a 16m load transportation.

execution time of 2 minutes, while the registration procedure using the PPFH features was accomplished within 25.3 *sec* (mean value of five runs). This rough approximation was close to the actual transformation matrix and the refinement procedure of the ICP had an execution time of about 2.2 *sec*. Last, the path planning algorithm was executed in 0.4 *sec*. Summarizing, the average duration for the registration and the route extraction was at 27.9 *sec* (note that for the same area this procedure is executed only once, if the user needs to assign a new goal position then it would only take 0.4 *sec* to extract the new path). The derived path using the D* Lite algorithm along with the respective 3D map (ground removed) is depicted in Fig. 6.

For evaluating the position accuracy, we performed an experiment with the loaded swarm traveling along a square with a side length of 4 meters for a total of 16 meters, performing also four 90° clockwise turns. The deviation of the vehicle's center control point along the X and Y axis with respect to time is reported in Fig. 7, and measured using the DU's lower SICK scanner. The vehicle's orientation in respect to its start position was also measured and noted as alpha. With speed set at 3m/sec, the overall movement was executed at 360 seconds with total accumulated error at 2.4cm and 25.3cm for the X and Y axis, respectively. In the latter axis, a slight constant Mecanum wheel slippage was

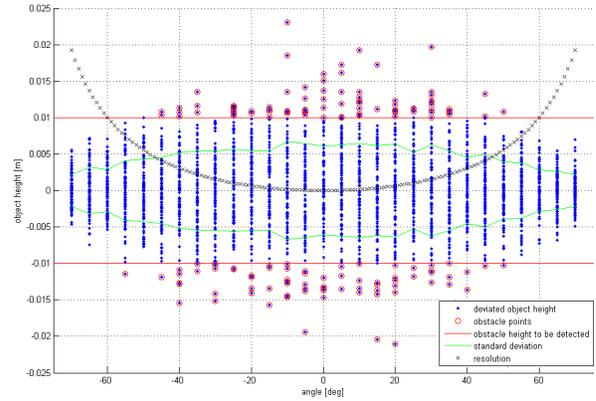


Fig. 8. Obstacle detection analysis with respect to tilt angle, measurement noise and angular resolution.

observed due to the fact that the ground was not fully even.

During the bogie deployment and movement, the local obstacle detection algorithm was evaluated in terms of sensitiveness and measurement noise. A crucial parameter for the evaluation was also the tilt angle of the laser ranger. The optimal angle can vary depending on the obstacle's height to be detected. The used testing configuration included 8cm for the vertical height of the light receptor, 40° tilt angle and ±10mm sensor measurement noise for distance measurements up to 1m. The results of the experimental trials are summarized in the diagram shown in Fig. 8. The diagram shows the distribution of object heights derived from the distance measurements with the laser scanner. The detected object heights were corrupted by the measurement noise in the distant measurements. The horizontal axis represents the angle measurements which are relative to the longitudinal axis of the bogie. The vertical axis represents the derived object height. Multiple distance measurements (blue dots) were performed. The standard deviations for each angle were also calculated (green marker). The minimum obstacle height (10mm) is shown as a red solid line. All measurements that detected an obstacle are marked with a red circle around a blue dot.

To verify AVERT bogies capability to lift vehicles, different types of vehicles were used to assess different tire size and weight combinations. The lifted vehicle had to be moved also along its longitudinal axis to verify that the drive motors are capable of displacing the loaded vehicle on an even surface with a maximum positive slope of 3%. In order to evaluate the maximum axle load lifting capability, a test load of 2000 Kg was also applied. The test loads were lifted 10 times in repetition while monitoring the lifting motor's power consumption and its driver temperature. The maximum loading tests were performed with a Renault van having empty gross weight of 2240 Kg, with 1340 Kg on the front axle and 900 Kg at the rear axle. The lifting unit was always fully expanded and retracted while performing the lifting procedures. As it can be seen in Table I and Fig. 9, the first three test loads were successful, however

TABLE I
AXLE LIFTING TEST SEQUENCES FOR VARIOUS LOADS.

Test Sequence	Test Load (Kg)	max. Power Consumption (W)	Motor Driver Temperature (°C)	
			Bogie #1	Bogie #2
1	900	197	25	22.5
2	1340	245	25	25
3	2050	260	25	25
4	> 2050	N/A	N/A	N/A



Fig. 9. Vehicle lifting tests for one axle: a) maximum load lifting capability at test load of 2000 Kg, b) close up of lifted tire.

loads over 2 tons introduced a swivel drive frame bending. The reason for the bending was traced down to elastic deformation of two dowel pin holes responsible for the correct alignment of the swivel drive frame and the lifting unit. In the first three successful tests, the standby current was at 1.2A with the no-load stroke current at 2.3A. In the fourth test, where the bending of the swivel drive frame was noticed, the lifting motor stopped moving as reached over-current condition. A repetitive groan was also caused by a spindle-nut combination of Bogie #1.

For testing the overall AVERT system, experiments were carried out in an indoor parking lot at the premises of Zurich University of Applied Sciences, Switzerland, and recorded in the accompanying multimedia material¹. All systems were deployed and tested in their respective capacities acting together for completing all the mission segments. Successful trials were performed reporting a full vehicle extraction between the initial position until the extraction point with a total covered distance of 20 meters. The final configuration of the bogies succeeded small obstacle overpassing without orientation misalignment, allowing also a wider choice of paths to be considered. Furthermore, accurate results from the 3D registration and path planning were reported with the scanning process having a standard execution time based on scan rate, while the registration procedure using the FPFH features was accomplished in a significantly lower time than the scan.

Table II provides the overall specifications of the AVERT system compared also to the most updated iCart II transportation system [4].

VII. CONCLUSIONS

This paper presented a new vehicle lifting and transportation system utilizing a new robot prototype. The developed robotic system entails a low profile compact design for easy

¹High resolution videos along with supplementary multimedia can be found at <http://robotics.pme.duth.gr/amanatiadis/avert/>

TABLE II
SPECIFICATIONS OF AVERT FULL BOGIE AND MRWHEEL [4].

	AVERT Bogie	MRWheel
Dimensions	1012 × 866 × 110 mm	1590 × 1262 × 538 mm
Maximum Velocity	15 m/min	30 m/min
Transported Car		
Maximum Weight	3500 Kg	2000 Kg
Minimum Wheelbase	1200 mm	1590 mm
Minimum Tread	1150 mm	1265 mm

access under conventional vehicles with high load capacity. On-board sensors allow autonomous tire detection, docking and local obstacle avoidance. A complete vehicle extraction and transportation in an indoor parking lot was performed, where its experimental results confirmed the validity on autonomous navigation, docking, lifting and transportation.

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