Kerberos - 3D undercarriage inspection system

Karel Košnar, Tomáš Krajník, Libor Přeučil

Abstract—The application describes automated laser-based undercarriage vehicle inspection system developed jointly by Czech Technical University in Prague (CTU) and VOP CZ, s.p. company. The system in question provides complete recovery of a full three-dimensional relief of a passing-over vehicle at reasonable driving speed. Its capability incorporates automated comparison of the reconstructed undercarriage model to previous scans of the vehicle from a database and identifies any additional objects. Unlike other systems, which rely mainly on high-resolution cameras, the Kerberos system employs laser range-finders. Thus this unique solution allows to find and label objects even in the cases, these exhibit similar, or the same surface color and texture as the background they are attached to. The system solution applies principles based on two- and three-dimensional shape reconstruction and registration methods, widely used in mobile robot localization and mapping. The cooperation of the CTU’s Intelligent and Mobile Robotics Lab with the industrial partner VOP CZ, s.p. allowed a smooth, fast and very efficient transfer of the aforementioned state-of-the-art methods into the security/inspection application domain product. The vehicle inspection scanner has currently been installed at several safeguarded facilities in Czech Republic.

I. PARTICIPANTS

The Kerberos system is a result of fruitful cooperation of well-established defense engineering company (VOP CZ s.p.) and Czech Technical University in Prague (CTU), herein represented by Intelligent and Mobile Robotics Laboratory. The university role was to suggest novel resolution principles of the given problem and to aid the overall system design and its implementation. Specifically, elaboration of software for data fusion, three-dimensional image reconstruction and additional foreign object identification has been in the focus of interests. The industrial partner overtook responsibility for electromechanical design, system testing and on-site installation.

A. Intelligent and Mobile Robotics group, IMR-CTU

The Czech Technical University in Prague (CTU), founded in 1707, is one of the oldest technical universities and currently the leading technical university in the Czech Republic with more than 45,000 of students enrolled in engineering courses. With over 1700 members of academic staff, it is also one of the largest research institutions in the Czech Republic. The Department of Cybernetics is recognized as an outstanding research center at the CTU. In 2000 the department received the “EU Centre of Excellence” award and in 2006 the prestigious European IST Prize by the European Commission. The Department includes over 80 academic staff and researchers, and over 30 Ph.D. students.

The Intelligent and Mobile Robotics group [1] is an integral part of the Department of Cybernetics [2] of the CTU. The conducted research of Intelligent and Mobile Robotics Group (IMR) comprises design and development of intelligent mobile robots, self-guided vehicles as UGVs and UAVs and advanced approaches to their control. The overall target is to advance the robot autonomy, via development of highly robust cognitive control systems for this kind of robots, or their swarms and to bring novel ideas into particular solutions. Four central topics are considered for the research interests of IMR group: Sensing of the environment, sensor data processing and data understanding, all leading towards automated world model building and updating. Used knowledge representations of the world are designed and optimized for planning of robot activities and for self-localization and navigation in real environments. The group is currently involved in several international projects with partners like the GRASP Laboratory, INRIA, Karlsruhe Institute of Technology or Graz Institute of Biology and many more. The technology transferred into this project has originally been derived from Simultaneous Localization and Mapping approaches used in mobile robotics.

B. Military Repair Facilities, VOP CZ

The VOP CZ, s.p. stands for a company that specializes in the field of civil and military equipment engineering and maintenance, engineering production and development. The company is mainly engaged in maintenance and repair of military and engineering equipment and production of heavy machinery. Recently, the company’s developmental activities are posed into modernization and production of military equipment and production of civilian engineering products. The VOP CZ, s.p. steadily enhances its engineering production for civilian purposes whose products are marketed on highly competitive international markets. Thanks to the expertise of its personnel and production capabilities, the VOP manufactures complex welded assemblies as well as completed products with high accuracy requirements.

The company is involved in international R&D projects within EDA or NATO and takes share in the major procurement programs of the Army of the Czech Republic. The VOP’s principal partners in the field of R&D are the Czech Ministry of Defense, Czech Ministry of Industry and Trade, National Security Authority, Defense and Security Industry Association of Czech Republic, NATO and EDA. It has more than 700 employees, who together provide a broad portfolio of professional services in the above mentioned areas.
The safety and security of selected facilities and areas become key issues in the nowadays community as activities of extremist organizations increase all over the world. One of the major treats is unauthorized entrance of persons and vehicles, carrying unauthorized or forbidden items like data storages, weapons and explosives into a secured area and physical attacks by e.g. explosives.

The personal security check points are equipped by door frame metal detectors and baggage x-ray screening devices which help to the increase the speed and reliability of the security check procedures. Practices from various public spaces as airports makes personal security field well researched and managed.

The vehicle screening procedures are more complex, since they cannot be based on metal detection methods. As it remains simple to attach anything to the undercarriage of a vehicle during the time it is parked in an area under insufficient surveillance, such as in public streets or parking lots at car owner's home, vehicle inspection procedures focus at foreign object detection. Nevertheless, routine security screening of vehicles still remains complicated, unreliable and slow. Present practice stops all the check point passing vehicles and manually/visually inspects the bottom of the vehicle. The undercarriages of vehicles are inspected using a mirror or a hand camera-monitor system. The manual inspection is slow, requires complete stop of the vehicle and thus does not allow fluent inspection at places with frequent traffic. Moreover, standard inspection procedures require extra space to buffer the vehicles for inspection. To remove the aforementioned drawbacks of manual vehicle inspection, automated systems, which capture the vehicle undercarriage image, are used at critical infrastructures. However, the attached objects might be designed to have the same appearance as the surface they are attached to. This would render them invisible to any camera-based inspection system.

To reduce the major risks of carrying unwanted items on the vehicle, the Kerberos system has been designed for automated checking for any changes on the undercarriage of the cars entering regularly safeguarded areas. The system highlights the changes to the operator for the further inspection. The core goal of the herein presented system is to handle the situations, where the majority of the cars enter a secured area on a regular basis, i.e. the cars belong to authorized personnel visiting the area frequently. This assumption allows the inspection process via systemic comparison of the vehicles undercarriage appearance and shape.

The basic design requirements are following:

- The inspected vehicle cannot be stopped.
- The average throughput exceeds 10 vehicles per minute.
- The system must operate in all-weather conditions.
- It has to detect automatically foreign objects even if they are camouflaged.

II. Motivation and Goals

Nowadays undercarriage scanning systems are exclusively based on high-resolution cameras. However, the capabilities of the systems differ significantly. The existing systems can be sorted into three categories respecting the applied principal approach to capturing the image data and their processing: streaming video approaches, global image gathering, global image with automatic comparison.

The first and simplest video streaming systems require full and uninterrupted attention of the operator. An example system of this class is the TRIGelectronics scanner [3], which provides a live video stream of the scanned undercarriage of the inspected car. The LED illumination is used to acquire clear, noise-free video in sufficient resolution. The still image is provided only on request of the operator. The Securitex VUC-Scanner improves the streaming functionality by wireless transfer of the video stream from small and portable scanning head to portable base unit with a CCD display (see Pic. 1).

Fig. 1. Securitex scanning head and portable base station.

The instance of the second category is the VACES-Car scanner [4] which delivers one global image of the whole vehicle. The system provides set of image post-processing filters to improve quality of the image. However, the image is distorted and warped by variations of the vehicle velocity and direction. Current and reference image of the same vehicle can be displayed for visual comparison performed by operator. However, the system is not capable to perform automatic comparison of the images.

Automatic comparison capability reduces the chances of security personnel overlooking potential threats by automatically identifying and highlighting any abnormality. An example of a system with such capability is the I2Security system [5], which provides undistorted image of undercarriage regardless of variation in speed. The system, based on two-dimensional imaging, automatically identifies any discrepancies in undercarriage or unauthorized modifications, such as hidden compartments, potentially explosive additional devices, etc.. The detected suspicious areas are highlighted. The iVACS system [6] introduces, besides the embedded and portable solutions, a mobile solution where the scanner is carried by a mobile robot (see Pic. 2). This allows to scan the stationary vehicles.

One of the most complex and sophisticated systems on the marked is delivered by Gatekeeper security [7], who
use either a fish-eye camera to build a global undercarriage image or a 'dual view' scanner, which allows to recover and automatically compare a 'virtual 3D' digital images (see Pic. 3). The scanner can be integrated into a complex security system with car recognition, X-ray scanner, explosive detector and biometric access control. The dual view capability allows to detect objects hidden hidden on top of an axel or a crossbeam.

![Fig. 2. Scanning mobile robot iVACS.](image)

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![Fig. 3. Gatekeeper security dualview scanner and virtual 3D image.](image)

Fig. 3. Gatekeeper security dualview scanner and virtual 3D image.

All of the aforementioned systems are based primarily on cameras. Thus, the systems would have problems to detect the attached objects, which are designed to have the same color and texture as the surface they are attached to.

IV. PROJECT APPROACH

The main idea of the solution is to detect foreign objects on the vehicle carriage, which might have the same appearance as the chassis parts they are attached to. Such objects may easily be invisible to vision-based systems regardless of the used principle of object detection. Rather than producing a high-resolution color image, the proposed system creates a three dimensional relief of the vehicle chassis. To identify the inspected vehicle, the registration plate of is captured and automatically recognized. Unambiguous identification of the vehicle then allows comparison of the current relief with the reference (or optionally other previous) records of the vehicle. Any discrepancies between the previous or reference carriage scans and current shape of the chassis are visually labeled and reported to the system operator. Subsequently, the user can rotate, translate and magnify the three dimensional surface and decide further on whether the detected additional object(s) represents a true security threat.

As in other systems, the scanner is part of a more complex system securing access to critical facilities. The system as a whole consists of a user-operated gate barrier, a license plate recognition module and the scanner itself. A vehicle-velocity indicator and speed and drive direction limiters assure proper pass-over direction and speed of the vehicle at the inspection time. The scanner itself comprises of three laser range-finding units - two scanners are buried in the ground and one is placed on the surface, see Picture 4. The underground range-finders have their scanning planes aligned into the vertical direction and scan the vehicle undercarriage. The on-surface laser range-finder has its scanning plane aligned parallel 5-9 cm above ground level and is primarily dedicated to determine approaching vehicle’s position, heading and velocity.

A. Principle of operation

The placement of individual system components is depicted in Fig. 5. As the vehicle approaches, its orientation and speed are delimited mechanically by speed limiting ramps, so it cannot move over the vertical scanner in an undesirable direction or speed. During the approach to the scanner, the horizontal scanning unit reads the vehicle speed. To allow vehicle speed adjustment into allowed range, the velocity values are provided to the driver via speed display in his/her field of view. As soon as the vehicle undercarriage reaches the vertical unit scanning plane, the system starts to gather measurements from both the vertical and horizontal scanners. The vertical scanners measure the chassis’ cross sections, which are collected into a three-dimensional point cloud. The horizontal range-finder data is used to determine the exact vehicle pose, which denotes necessary information to properly align the chassis cross sections within the point cloud coordinate system. As the vehicle leaves the vertical scanning plane, its license plate image is captured by a camera and the vehicle is identified. The captured point cloud is post-processed to remove various artefacts and re-sampled to achieve uniform spatial resolution of the relief recovery procedure. Finally, the system assigns the processed three-dimensional image data to a database together with the vehicle ID (recognized license plate) and displays corresponding reports to the system operator.

If the database contains a reference (safe) chassis scan from one of the previous vehicle passes, a comparison routine is carried out. In other words, firstly, components of the current scan are registered with the safe three-dimensional point cloud by means of standard 3D registration techniques, as commonly used in mobile robotics domain. Subsequently, the registered to-time scans are searched for differences, which are evaluated by a series of image operations used in a computer vision domain. Finally, suspicious differences of the reference (safe) and the current vehicle scan are marked.
Fig. 5. System components at the secured gate.

by a distinct color and offered as hypotheses on possible security threads. The system user can set the viewing angle and zoom in/out both the reconstructed surfaces to obtain a clear, close view of the critical areas and properly undertake the final decision whether the detected objects truly represent a danger.

![Current 3D scan with indicated foreign objects.](image1)

(a) Current 3D scan with indicated foreign objects.

![Safe 3D scan from a previous vehicle's pass.](image2)

(b) Safe 3D scan from a previous vehicle's pass.

Fig. 6. Threedimensional scan comparison.

Nevertheless, the system does not necessarily require permanent and immediate attention and decisions of the operator. Rather than that, the cases of multiple passes of vehicles at once (convoys of up to 20 vehicles) are stacked in a queue within the evaluation system and therefore can be processed later on.

V. RESULTS OF RESEARCH AND DEVELOPMENT

Apart from the system itself, the project provided valuable data regarding long-term, all-season operation of laser range-finding equipment in outdoor areas. The obtained data allowed design of extremely robust vehicle position and velocity estimation methods capable of dealing with harsh and adverse weather conditions, such as rain, snow and even a light fog. Moreover, a novel technique of fast three-dimensional shape registration, which does not completely rely on the shape rigidity, has been designed and implemented. The most suitable data processing methods, which infer potentially dangerous objects from the differences in registered shapes, have also been successfully verified.

Applying the previous methods and tools and speaking in quantitative measures, the Kerberos system achieves the following performance:

- Vehicle inspection speed levels up to 15 km/h with object resolution in order of few centimeters (whereas longitude resolution component varies with the vehicle velocity).
- Threedimensional reconstruction, chassis comparison and shape visualization in less than two seconds allows to inspect more than 20 vehicles per minute.
- Reliable operation in adverse weather conditions including snow and rain.
- Very low failure-rate in terms of either missing a foreign object, or reporting a safe vehicle as occasionally dangerous. Achieved values depend on the system parameters setup for particular application and can be influenced by the user.

The aforementioned parameters of the designed system do fully match the intended project goals.

![Kerberos system at VOP CZ facility in Nový Jičín.](image3)

Currently, one instance of the system is installed at VOP CZ facility and another few others are used to safeguarding of Czech national security authorities.

VI. ACHIEVED INNOVATION AND COMMERCIAL IMPACT

The result of this project is the only (up to our knowledge) vehicle undercarriage inspection system in the world which can automatically detect and suggest hypotheses on foreign objects even if their surface closely resembles the surface they are attached to. This performance has been achieved via reconstructing of full three-dimensional model of the carriage surface from direct range-measurements. The chosen approach completely cancels out possible performance failures originating from visual similarity of the searched objects with the carriage background. This capability poses the Kerberos system supreme to any pre-existing automated inspection
system based on color or monochrome camera sensing. The current implementation of the three-dimensional reconstruction and foreign object detection algorithm allows to process up to 20 vehicles per minute. Therefore, the processing speed is sufficient for routine inspection procedures even at frequently visited areas. Moreover, the system resolution, speed and detection reliability remains fully scalable and it can easily be fostered by adding more laser range-finders and cameras.

The expected commercial impact correlates with potential application classes.

System’s ability to automatically inspect for likely threatening objects disburdens the security personnel from tiresome task of manual checking of passing vehicles. The important related issue is seen also in substantial improvement of the inspection performance (speed) at decreased rate of failures. Generally, further development of the system towards its customization for particular specific applications (i.e. optimizations on product costs, system mobility, inspection speed and resolution improvements, etc.) has already been launched.

VII. HANDLING OF INTELLECTUAL PROPERTY RIGHTS

All the research and development activities concerning completion of the Kerberos vehicle inspection system have been done in a framework of a contract between VOP CZ, s.p. and the Czech Technical University in Prague. The agreement in question follows the standard conditions of Commercial Law of the Czech Republic. By completing the above agreement, the partners have agreed on transferring all the within contract created intellectual property rights and owner rights onto the VOP CZ, s.p. company. To time, VOP CZ, s.p. company stands for exclusive owner of the current Kerberos system solution.

VIII. COOPERATION AND BENEFIT

Neither of the partners alone would be able to complete the described project successfully. In that terms, CTU represented by Intelligent and Mobile Robotics Group benefited from long-standing experience of VOP CZ, s.p. partner in machinery design, construction and superb knowledge of the security and defense market requirements. Moreover, the VOP CZ, s.p. was able to set up an outdoor testing facility, which allowed gather real measurements to develop, test and verify the data processing methods on real world data, to prepare realistic all-whether conditions as well as to perform exhaustive testing of the final product before releasing it on the market. The data, which were gathered by VOP at their facility over a long period of time, proved to be very valuable for design of robust localization, reconstruction and registration methods.

On the other hand, the Czech Technical University partner brought up the innovative approach into the solution - not to rely on the standard approach using high-resolution cameras, but ground the system on active range-finding technology. The experience with laser range-finding technology allowed fast prototyping of the electromechanical design of the scanning unit, depict potential hazards and estimate system operating parameters. Most of the system core software methods, i.e. the data processing, localization of the vehicle, three-dimensional reconstruction and shape registration algorithms were particularly available at the university partner. Therefore, the core methods did not have to be implemented from scratch. Rather than that, their reference implementations were tested with the provided prototype data and potential methods candidates were efficiently selected for succeeding tests. This approach assured high efficiency of achieving the desired solution and allowed to complete the innovation and technology transfer within a horizon of 4 months.

Moreover, there were identified certain other side impacts for the university partner - the Intelligent and Mobile Robotics Group. Execution of the joint academia and industry development procedure opened a possibility to run long-term experiments and gathering realistic measurements in outdoor environment over long periods of time. The access to real data and the collected measurements represent highly valuable testing data-sets and driving force for both, further development of Kerberos system, as well as for academic research purposes.

REFERENCES