Semi-automated Handling of Manhole Covers for Tank Wagon Processing Using Industrial Robots

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Abstract—In this paper a solution for the handling of tank wagon manhole covers using industrial robots is presented, which will be used in automated loading stations for flammable liquids. Currently only the actual loading process is automated, leaving the operator with a number of unergonomic and hazardous tasks. The main obstacle for the automation of the process is the heterogeneity of the processed tank wagons and manhole covers. The presented approach supplies a procedure for identification of key geometric features of the wagons and a mechanical setup providing the required flexibility for the actual handling process. Additionally a suitable control structure and Human-Machine-Interface for the station had to be developed, as the facility operators have no robotic experience but frequently have to interfere with the system to verify and adapt the targets given to the robot system. The developed system has been validated in a prototype setup and is currently transferred to the actual industrial facility.

I. INTRODUCTION

The transportation of petrochemical products, like gasoline or diesel, is done mainly via railway, using tank wagons (see Fig. 1). In the refinery, for which the robotic solution, described in this paper, was developed, approximately 60\% of the products are transported with tank wagons. The production of petrochemical products is automated to a large extend, the same is true for the actual process of loading the tank wagons. But directly before and after the loading process a number of process steps have to be executed manually. These include: Controlling the wagon identification plates, opening the manhole cover on top of the wagon (which is used to load the liquids) and inspection of its seal, depletion of remaining liquids via valves on the bottom and – after the wagon is filled – closing of the cover.

The execution of these manual steps inherits a number of ergonomic and immediate risks for the operator. The loading process is carried out outside, resulting in ambient temperatures from -20°C up to +35°C, besides being exposed to rain or snow. The access to the manhole covers is inconvenient and the actual opening process involves heavy lifting and stooped postures, increasing the risk for spinal injuries. In addition, due to the processing of flammable liquids, parts of this work are performed in explosive atmospheres. As the tank can be pressurized, there is a risk for the operator, being hit by the cover, once opened, or even to be thrown off the wagon. An automated process could avoid or at least reduce these risks for the operator.

Although the tasks preceding and subsequent to the loading of the tank wagon are hazardous and thus there is a strong need for an automation of the process or for technologies assisting the operator, up till now the tasks have been carried out completely manually. The main obstacle for automation of the process is the heterogeneity of the processed tank wagons. They vary in total volume and dimensions and (which is especially interesting for the loading process) in position and design of the manhole covers on the top and the valves on the bottom. This diversity is due to different wagon manufacturers, a patched age distribution (wagon models from 1970 till now) and modifications of the wagons during repairs. As the tank wagons are mostly rented, modifications of the wagons themselves, in order to unify the mechanical features, are not possible.

In order to implement an automated system, solutions for recognition and handling of varying wagon geometries are required. As the number of possible variants is not certain, it is likely that interference of the operator will still be required in certain cases. To enable such interference, suitable interfaces have to be defined and implemented. Due to the varying wagon geometries a robotic solution to unburden the operator was advised. However the operators in the considered facility inherit no robotics experience. Therefore additionally to the technical problems which have to be solved for a (partial) automated execution of the considered tasks, the ‘new’ technology has to be introduced to the operators – preferably to be perceived as simplification measure and not as additional complication of the process. Human-centered design of the new process sequence and the user interfaces can avoid rejection of the robotic solution by the operators – preferably to be perceived as simplification measure.

The paper is structured as follows: In Sec. II an analysis of the current manual process is performed, in order to identify...
suitable automation approaches. In Sec. III the development of the automated system, consisting of mechanical design (Sec. III-A), sensor-based feature identification (Sec. III-B) and interface between automated system and operator (Sec. III-C) is described. The paper ends with conclusions and an outlook on the ongoing work in this facility.

II. ANALYSIS OF THE CURRENT MANUAL TASK

A. Process analysis and boundary conditions

The overall layout of the loading station is depicted in Fig. 2. The wagon track is split into four separate tracks, each processing different products. On each track groups of 10–15 wagons are handled, depending on wagon size. As the performed steps on each track are identical, only the procedure on one track is described in the following. Central reference point of the overall station is the automated loading station (Fig. 2-C), where the wagon about to be filled has to be aligned, determining the positions of all coupled wagons as well. There are two loading stations; each processing two tracks. The loading process takes approximately 10 minutes per wagon, thus determining the overall cycle time. Preceding to the loading the operator first has to identify each wagon using its registration plate. Then he climbs up the wagon, opens the manhole cover, inspects its sealing and checks the wagon for potential rest material (Fig. 2-A). In order to open the manhole cover the operator currently has to step on the tank wagon and has to loosen the fastening mechanism (often a number of tommy screws, see examples in Fig. 4) in a stooped posture. As the operator is standing on a light grid, the elements he has to handle are located on level of his feet or below. High forces have to be brought up by the operator (details see Sec. III-A), as the fastening mechanisms often are dirty or rusty or can be frozen. The same problems apply to the subsequent lifting of the cover: The cover itself weighs approximately 25 kg. Additional lifting force is required if the cover is sticky or if there is negative pressure inside the tank wagon. The converse case is even more dangerous – if the tank wagon is pressurized (e.g. because it was heated up by the sun), the cover can spring open once fastening is loosened, hit the operator or throw him off the wagon.

After opening the manhole cover, the operator returns to ground level and depletes any fluids remaining in the wagon (Fig. 2-B). The required handling elements are located on the bottom of the wagon in a height of approximately 1 m (some examples can be seen in Fig. 3). After finishing the preparation of the wagon for loading, the operator walks to Station E to close and fasten the cover of the wagon, which has been loaded in the previous cycle.

As the goal of the automation is to avoid direct risks and unergonomic poses for the operator, a closer analysis of the executed manual tasks, evaluating these risks, was performed. As result of that analysis it became apparent that the manual tasks to be performed on the top of the tank wagon (opening and closing of the cover) inherit the main health and safety hazards. The tasks performed on ground level (depletion of remaining liquids, readout of the identification plate) are carried out in uncritical postures and do not pose immediate threats for the operator. On the other hand the control elements on the bottom vary greatly in type, geometrical features and position; the required operations are complex and largely dependent on the wagon type. This results in a process hardly possible to automate with reasonable developmental and equipment effort. For these reasons the presented concept is focusing on automation of the operations performed at the upper level, starting with automation of the cover opening process, where most immediate hazards and the highest workload can be found.

Although the features of the wagons around the manhole cover are more consistent, there is still a significant heterogeneity to be handled by the automated manipulation process. An inquiry regarding the wagon geometries and in particular the properties of the manhole covers was carried out (ca. 200 wagons were analysed). This inquiry resulted in a sub-division of the manhole covers into three groups, each requiring a different treatment by the automated solution (see Fig. 4).

Type a contains all manhole covers which are conform to DIN EN 12561-6 [1]. Additionally covers are included, which are not conform to this standard, but have four tommy screws equally distributed on the perimeter of the cover. To open a cover of type a, the screws have to be loosened and folded away before the cover can be lifted. Shape and position of the cover handle can vary.

Type b covers have a semicircular handle above the cover, with a rotational joint on one side and one fastening screw on the other side of the cover. When the screw is loosened, it is used as handle to lift the manhole cover.

Type c covers do not share common design features. This group consist of a variety of special covers and fastening mechanisms, which cannot be assigned to one of the other categories. Number, kind and position of the used screws, toggles or handwheels on the manhole cover vary greatly (see for instance the rightmost bottom cover in Fig. 4). Covers of that type are often the result of modifications or repairs of the tank wagon.

Approximately 75 % of the manhole covers can be assigned to category a, another 10 % to category b. The remaining 15 % are summarised in category c. As the basic fastening mechanism for category a and b is the same and
only the number and position of tommy screws is varying, it was decided to aim at a solution for these two categories first, thus being able to open approx. 85% of all tank wagons autonomously. During the inquiry of the geometrical features a number of other process characteristics were ascertained, including loosening and tightening torques, size and position of the tommy screws, required forces to open and lift the cover, the final opening angle of the cover and the relative position of the manhole on the tank wagon (see Sec. III-A). The determined values were used for dimensioning of the mechanical design of the automated system, which is explained in Sec. III-A. Important additional requirements for the automated system were, that it has to withstand the environmental conditions (outside, ambient temperatures from -20°C up to +35°C) and that its components have to fulfill standards for devices intended for the use in explosive atmospheres, like [2], [3], [4] and [5].

Besides the technical properties of the process, the intended users – the system operators – have to be considered. In this particular application the system operators have no previous experience with industrial robotics at all. They are Novices in this field, while they are skilled (or even Experts) regarding the actual process (user group specification according to [6]). This combination of technology experts, but robotic novices is encountered inevitably when introducing industrial robots to new application areas; in particular when those are carried out in SME environments. In this specific application there is no need for frequent reprogramming of the robot, as the general task sequence will not change over a long time period. Therefore the main programming of the robot can be done in a conventional way. However the user frequently will have to interact with the system, modifying or confirming details of the path. The system therefore has to be designed such, that this interference is conveniently supporting the task execution and thus encourages acceptance of the system. It is important to avoid situations like paradoxical intervention [7]: The human operator only intervenes in situations that cannot be handled by the automated system, but since he does not understand the underlying functioning of the system, the operator is incapable of applying appropriate countermeasures. Provision of a sufficient information exchange across the Human-Machine-Interface (HMI) is seen as crucial to avoid such scenarios [8].

In order to improve acceptance for the system and to support its beneficial use, faulty (user) actions or negative implications of system errors on the user should be avoided. Rules of action, as provided in [9] (similar design principles can be found in ISO 9241, Part 110 [10] or ISO 11064, Part 5 [11]) can help designing a system compliant to these demands. The most important rules for the system developer, applicable to the presented use-case are:

1) Design functionalities considering the user: The main goal is the support of the user task. The offered functionalities should meet his needs and information displays should be consistent with his expectations.

2) Reconsider system complexity: Reducing complexity can reduce vulnerability to failures and increases comprehension of system sub-functions for the user. A better understanding of the system functionality leads to less faulty actions and more targeted user corrections in case of system errors.

3) Make the main functionalities obvious: The user can immediately perform targeted actions; time required to learn how to operate the system is reduced.

Hoppe [9] also gives indications for the user to avoid technological stress, which can be partially supported by corresponding system design. For instance unpredictable system errors or exceptions, if not clearly identifiable as such, often result in the user (wrongly) assuming to have performed operating errors, thus generating uncertainty in usage of the system. The European Agency for Safety and Health at Work even assesses the complexity of new processes and the poor ergonomic design of the respective visual display unit (VDU) workspaces as (emerging) human factor risks [12].
For the application of tank wagon cover handling a suitable control structure has to be implemented, allowing users with no robot programming background to evaluate and (if necessary) correct the varying task steps. Also an early inclusion of the operators in the design process was chosen to reduce the required design iterations and to gain acceptance for the automated solution.

B. Review of related existing automated solutions and assistance technologies

A number of systems for automated loading of tank wagons with liquids are available (like described e.g. in [13]), but all cover only the loading process itself and manipulation of the filler neck (to compensate for position tolerances of the manhole) via a control station. The preceding and subsequent manual steps, which pose the threads for the operator, which have been discussed in the previous sections, are regularly not covered. However, similar issues as in the topic of tank wagon loading occur in the area of autonomous refueling of vehicles (e.g. aircrafts): Fuel tank covers with varying geometries have to be identified in order to open and close them. Since several years the use of robots for such applications has been discussed (e.g. in [14]), as they offer the flexibility required to adapt the tool movements to the changing geometries. Identification of the geometry features (positions of screws which have to be unfastened to open the aircraft panel, see [15]) is mostly done using vision systems and proximity sensors.

Supportive handling devices (also in form of hand-guided robots) for screw loosening and lid opening, which allow manual task execution in uncritical body postures, were investigated. However such devices can only lower the ergonomic risk of the process, while the operator is still exposed to the explosive atmospheres and the risk of being hit by the cover or thrown off the wagon. Therefore devices for support of the manual task execution should only be a temporary improvement, until this task is taken over by the robotic manipulator.

III. DEVELOPMENT OF THE AUTOMATED SYSTEM

Based on the investigations described in Sec. II, a concept for robot-based assistance for the operator of the tank wagon loading station was developed. For the previously described reasons the robot is planned to take over the tasks on the upper tank wagon level. These tasks should be executed automatically as far as possible and otherwise request operator instructions in a suitable way. The mechanical gripper design, positioning and motion planning of the robot is described in Sec. III-A. The respective sensor integration and proximity sensors.

A dedicated end-effector was designed, which is able to form-fit grab all potential tommy screws (the complete gripper prototype is depicted in Fig. 5). The capabilities of this end-effector were validated in the real industrial process on over 120 tank wagons. The end-effector is driven by a compressed air-motor (chosen over an electric drive due to explosion prevention). This motor can apply a maximum torque of 150 Nm, which covers most of the loosening torques encountered during the inquiry described in Sec. II-A. If higher torques are necessary (e.g. in case of rust on the screws or if the screws have been tightened too much), the motor can be locked and the loosening torque can be applied by the 6th axis of the robot, which is aligned with the rotational axis of the end-effector (see Fig. 5). Depending on the deployed robot model screws with loosening torques of up to 500 Nm can be processed. After the whole manhole cover is unfastened, it is opened by the robot. As the geometry of the cover handles varies in position, form and size, the robot is gripping the cover using a magnetic gripper (which can be turned on and off via pressurised air). All gripper components are designed or have been modified for the use in explosive atmospheres. The robot itself is not inherently safe for the use in such environment, but retrofit solutions (protective covers for the joint motors or the whole robot arm) that solve this issue are available on the market.

It can happen, that there is a negative pressure inside the tank wagon, resulting in forces up to 600 N required to lift the manhole cover. To ensure a reliable opening of the cover,
a pressure equalisation is generated in the following way: Before the last screw is loosened, it is purposefully tightened. As the other screws are already opened at this point, this causes a flexible deformation of the cover, generating a small gap between cover and tank through which air can flow into the tank. All mechanical concepts, the robot movements required for opening of the cover as well as the data acquisition necessary for identification of position and size of the manhole cover and its screws (as described in the Sec. III-B) have been integrated and tested in a prototype cell at the Brandenburg University of Technology, Chair of Automation Technology (see Fig. 6). Segments of real tank wagons have been used for the validation experiments.

B. Detection of geometrical key features

An automated handling of the manhole cover requires identification of several geometrical features of the tank wagon:

- The position of the tank wagon on the track,
- the relative position of the cover on the tank wagon (can vary along the wagon length and width – not all are aligned centrical – as well as in vertical direction),
- the positions of the tommy screws with respect to the cover center point,
- the opening direction of the cover as well as the position of the cover’s rotational axis,
- a suitable point to position the magnetic gripper to be able to lift the cover.

The identification of the listed features requires either a three-dimensional measurement or the derivation of three-dimensional information by combination of sensor data. Methods based on pure image processing encounter critical problems due to the strongly varying process conditions (illumination, wagon color and its degree of pollution). The usage of laser triangulation sensors requires too much time for movement of the sensor, as the available measurement ranges are comparably small. Additionally they are not available in ATEX [2] compliant versions. Measurement systems with ranges of several meters are too expensive for a permanent installation. Stereo based vision systems supply a large measurement range and can be modified to fulfill the criteria of the ATEX directive. For the development of the detection algorithms a modified Kinect sensor\(^1\) was utilised, which was integrated into the robot gripper (see Fig. 5). Industrial products utilizing the Primesense technology used in the Kinect are available\(^2\). However the algorithms for feature identification are not limited to this sensor by principle. The NI LabView Vision Development Module\(^3\) was used for processing of the depth information.

The complex identification task was subdivided in a number of consecutive tasks. The start of the measurement procedure is triggered, when the wagon in the loading station is positioned correctly (Fig. 2, station C).

In the first step the robot is moving along the linear rail, parallel to the wagon track, in order to identify the origin of the tank wagon using the depth sensor. Then it moves along the wagon, scanning for the manhole (circular elevation of approx. 60 cm diameter). The preceding step had been introduced, as the algorithm for identification of the manhole sometimes identified false-positives, when being between two wagons and the algorithm for identification of the wagon origin allows higher speeds for moving the robot along the rail (approx. 1.5 m/s). When the origin of the wagon has been identified, the (slower) search for the manhole can be limited to ±2m around the wagon center. After it is identified, the sensor depth image is cropped such that it only contains the manhole cover and its fastening screws. The position of the screws is identified by searching for geometries along the manhole diameter in the cropped depth image (see Fig. 7 for the different identification steps).

Two search algorithms, optimized for type a or b covers are implemented. The wagon type is previously provided by the operator (see Sec. III-C). For each identified screw afterwards the following steps are executed: To minimize the error introduced by the skew between depth sensor and tommy screw the robot first positions the gripper (including the depth sensor) directly over the respective screw. The depth image then again is cropped to the approximate area around the screw center. Within this area the edges of the screw toggles and thus their orientation is detected. After all detected positions as well as a free area for positioning of the magnetic gripper have been approved by the operator (see Sec. III-C), a compensation of the sensor error (image errors of the lens, calibration of the depth values) based on the Oulu-Method\([^16\)] is applied. The detected positions are

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\(^1\)http://www.xbox.com/en-us/kinect/
\(^2\)see e.g. http://www.fotonic.com/
\(^3\)http://www.ni.com/labview/vision/
then transferred into the robot coordinate system (the relative position of the sensor on the gripper is calibrated once and stored in the data processing system) and are used to open the cover as described in Sec. III-A. During a spot-check in the refinery environment the geometrical features of all sampled wagon covers were correctly detected using this method.

C. Interaction between operator and automated system

The main guideline for the design of the new assisted process and the respective interaction between the operator and the robotic system was, that the operator has complete control over the process; he monitors, controls and aborts (if necessary) the main processes. For this a sound understanding of the overall task is required. The system has to enable a reliable decision making (e.g. ‘Are the features identified for the automated opening ok or not?’) by providing sufficient information and thus should foster the learning process. As the process execution via the robot is a new development, it is likely that optimizations can be identified by the process experts during usage, which is more substantial the better the functionalities of the automated system are understood. Despite the defining position of the operator within the process, the automated system has to prevent the execution of unsafe or incorrect commands.

The main steps of the new process sequence are depicted in the scheme in Fig. 9. Required starting point is that one wagon is positioned in the loading station (see Fig. 2-C), as this influences the position of all other wagons on the track and the automated steps cannot be performed while the wagons are moving. Once the wagons are positioned correctly, the operator starts the handling process by selecting the cover type of the wagon, which has to be opened next, based on a RGB image (see Fig. 7). The identification number of each wagon has automatically been read using OCR (Optical Character Recognition). An example for such an identification number can be seen in the leftmost picture in Fig. 8. All information gained during the identification process are stored in a database similar the one described in [17], referenced by that number. If the tank wagon already has been processed in this facility, these stored information can be used for validation of the values detected by the automated system.

In case the wagon number is known (most wagons are in subsequent station (Fig. 2-A2, see also in Fig. 10). But for most covers (approximately 90 %) the identification procedure is carried out and the detected positions for screws and gripper attach point are displayed to the operator along with the values read from the database. The operator has to approve the detected poses (which are displayed to him as shown in Fig. 7, steps 2–4) before the opening process is initiated. When large deviations between the measured and the database entries are detected, the respective features are highlighted to the operator (reasonable tolerance values have to be evaluated during usage in the original facility). If the operator does not approve the detected positions for any reason, he can manually adjust the critical features or chose automated station (Fig. 2-A1) and has to be opened manually in the subsequent station (Fig. 2-A2, see also in Fig. 10).
to use the stored values instead. Depending on his choice, the database is updated with the currently used values. An update of the database entry can become necessary, when a cover was modified (usually during repair or maintenance). In case the cover was modified in a way that does not allow an automated handling (for instance when a tommy screw was replaced with a hand wheel) and by mistake the identification process has been carried out nonetheless, the operator still can block the wagon from automated handling at this point. After the cover has been opened, the operator walks to station B (see Fig. 2) and depletes any remaining liquids from the wagon in that station.

In practice the workflow described here will be distributed between three operators: One in a control room, controlling the automated stations and two on ground level, taking over the depletion of the tank wagons as well as the occasional cover opening and closing for the wagons that cannot be processed by the robot. The operator in the control room controls all four tracks, while the operators on ground level each are responsible for two of the tracks (due to the time required for the manual tasks).

The security concept is depicted in Fig. 10. Operator and robot do not share a common workspace, so despite the frequent interference of the operator, there is no collaboration in the sense of ISO 10218-2 [18]. Due to the structure of the facility a fixed fence is not possible, therefore a number of light grids is used to secure the cell against access during operation. The grid can be partially deactivated in the area of the manhole cover, so that the robot can access the manhole cover. A combination of manual and automated process would have been possible in principle, but within the facility enough space is available for two subsequent stations (automated and manual) – this setup is also beneficial with respect to the overall cycle time, as it allows parallel processing in both stations. Currently the robot cell and control system are prepared to be set up at the refinery facility to test the complete system within the actual loading process.

IV. CONCLUSIONS AND FUTURE WORK

The problem to reliably identify and handle different manhole covers on tank wagons has hindered the automation of this unergonomic and risky process. Based on a statistical inquiry the expected process and boundary conditions have been ascertained. An identification procedure for the key geometrical features and a mechanical concept for handling the manhole covers using an industrial robot has been developed and validated in a prototype setup. The functionality of critical parts of the cell (end-effector, sensor system) has previously been verified in the actual industrial environment. A control system incorporating the operators and utilizing their capabilities has been implemented, reducing the risks during the manhole cover opening for the operator to approximately 10% compared to the manual system. The first pilot application of a complete cell to work in the actual facility is currently in preparation. After a successful trial for opening of the manhole covers the concept will be transferred to the station where the cover is closed again.

For the developed solution it was not necessary to allow a shared workspace or a physical contact between human and robot. However similar boundary conditions as in the considered facility can be found in other areas where (collaborative) robotic applications will expand to: Together with the capabilities of the utilized robots a suitable programming and control system – which has to be adapted to the experience and capabilities of the respective process experts – has to be developed. In the described case acceptance of the system was more related to proving the capabilities of the robotic solution ("Will it work reliably?") as towards the robotic technology itself. This was due to the fact that this solution reliefs the operators from an unpopular and hazardous task. In other cases probably more efforts are required to convince the users from advantages of robotic technology.

Ongoing work for this development includes the connection of the tank wagon database to the existing manufacturing execution system. Longterm experience using the system in the production environment has to be acquired. Once the complete system is installed at the refinery facility, the identification, handling and control systems will be respectively evaluated and iteratively improved. Future research will also focus on possibilities for handling of the remaining tank wagons which currently cannot be handled automatically.

REFERENCES


Workshop Robotic Assistance Technologies in Industrial Settings, http://lasa.epfl.ch/workshop_ratis/
IEEE/RSJ International Conference on Intelligent Robots and Systems, Nov. 3-8, 2013, Tokyo, Japan.