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KUKA Innovation Award Application

Autonomous Picking & Palletizing (APPLE)

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Summary: The APPLE project is located in a logistics setting, where a number of goods need to be commissioned in a warehouse automation scenario. We developed a mobile manipulation system which is capable of autonomously: i) picking up an empty pallet; ii) navigating to a designated load area where simple target objects (such as boxes, bottles, cans etc.) are stored on another pallet; iii) using the KUKA LBR iiwa manipulator, equipped with an underactuated gripper, to pick up a subset of the target objects and place them on the commissioning pallet carried by the platform; iv) transporting the loaded goods to a designated target area. The logistics sector is one of the fastest growing branches of robotics and as such presents an important application domain for the KUKA LBR iiwa. Thus, the Autonomous Ground Vehicle (AGV)-based mobile manipulation system developed in APPLE will serve to demonstrate potential applications and facilitate the launch of future projects.

February 15, 2015

1 Team Description

The APPLE project is carried out at the Center for Applied Autonomous Sensor Systems (AASS) at Örebro University, Sweden. AASS organizes research and graduate studies in Autonomous Systems at Örebro University and is one of the appointed research environments of the Swedish Knowledge Foundation (KKS). AASS has participated in EC networks of Excellence, FP6/FP7 STREP and IP projects and is coordinating the H2020 project SmokeBot[1]. Directly relevant for this application are the FP7 IP projects HANDLE[2] and RobLog[3], which were dealing with autonomous grasping/manipulation of objects and unloading of shipping containers, as well as the KKS projects ALL-4e-HAM, ALLO, MALTA and SAUNA which were focusing on the automation of industrial AGVs. For an overview of some of the relevant projects, see `http://www.youtube.com/watch?v=L1EyUCGPstk`.

The principal investigator in APPLE, Professor Achim J. Lilienthal, is full Professor at AASS where he is leading the Mobile Robotics & Olfaction Lab. His main research interests are mobile robot olfaction for inspection robots and 3D perception, robot vision and safe navigation for professional service robots in logistics applications. Other researchers from AASS who are involved in APPLE are Dr. Robert Krug (key expertise: grasping and control [1, 2, 3]), Dr. Todor Stoyanov (mapping and 3D perception [4, 5, 6]), Dr. Henrik Andreasson (AGV navigation) [7, 8, 9]) and Rafael Mosberger (people detection) [10]. Engineering expertise for the demonstrator assembly is given by Per Sporrong, Bo-Lennart Silfverdal, Joakim Larsson and Bengt Åsberg.

Support for the grasping hardware used in APPLE is provided by Vinicio Tincani, Prof. Antonio Bicchi and Assoc-Prof. Gualtiero Fantoni from the Centro E. Piaggio at the University of Pisa who are leading experts in the development and design of innovative grasping devices.

2 Motivation and Objectives

The increasing need for fast and flexible commissioning (*i. e.*, order picking and collection of unstructured goods from storage compartments in warehouses) in logistic scenarios has created substantial interest for autonomous robotic solutions. This was also evidenced by a recent BBC investigation into a UK-based Amazon warehouse[4], which highlighted that the dull and strenuous nature of commissioning could cause mental and physical illness in human workers. Amazon themselves took action by organizing their first Picking Challenge at ICRA 2015.

The APPLE project addresses the following important sub-task chain which occurs during commissioning in prototypical warehouses: picking of goods from a storage location, subsequent placement on a standard EUR-pallet and transport of the filled pallet

[1] January 2015 to June 2018;

[2] February 2009 - January 2013; `http://www.handle-project.eu`

[3] February 2011 - January 2015; `http://www.roblog.eu`

[4] `http://www.bbc.com/news/business-25034598`

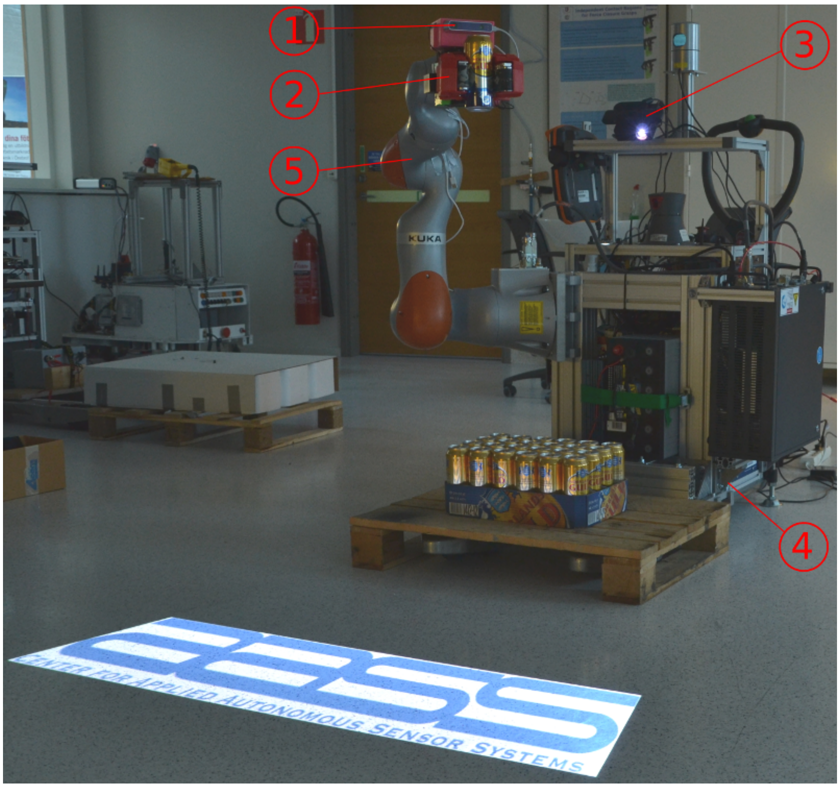

Figure 1: *The APPLE demonstrator:* A KUKA LBR iiwa (5) is mounted on a CitiTruck AGV (4). The projector (3) is used to display path information during AGV driving. The depicted Velvet Fingers gripper (2) is a further developed and smaller version of the gripper used in the FP7 IP project RobLog. Each of the grippers two fingers has a planar RR manipulator structure with two rotary joints and active surfaces which are implemented by conveyor belts on the inside of the two phalanges. The mechanical structure of each finger is underactuated and comprises one actuated Degree of Freedom (DoF) for opening and closing and two DoF for the belt movements. If, during grasping, the proximal phalanges are blocked by an object, the grippers distal phalanges continue to wrap around and envelope it in a firm grasp. Object and pallet detection is done with an ASUS Xtion Pro camera (1) which is mounted on the gripper's palm.

to a target location. The process has to be carried out in a manner which is safe for humans operating in the same environment. To this end, we assembled a suitable mobile manipulation and transportation platform by equipping a light-weight KUKA LBR iiwa arm with our Velvet Fingers gripper [11] and mounting it on a forklift-like Linde CitiTruck AGV (see Fig. 1). The main objective of the APPLE project is to develop a system which is capable of autonomously: i) picking up an empty pallet; ii) navigating to a designated load area where simple target objects (such as boxes, bottles, cans etc.) are stored on another pallet; iii) using the manipulator to pick up a pre-selected subset of the target objects and place them on the commissioning pallet carried by the platform; iv) transporting the loaded goods to a designated target area (see Fig. 2 for an overview of the application scenario). Accomplishing the project objectives required to address a number of problems, most of which were solved by adapting existing technology and

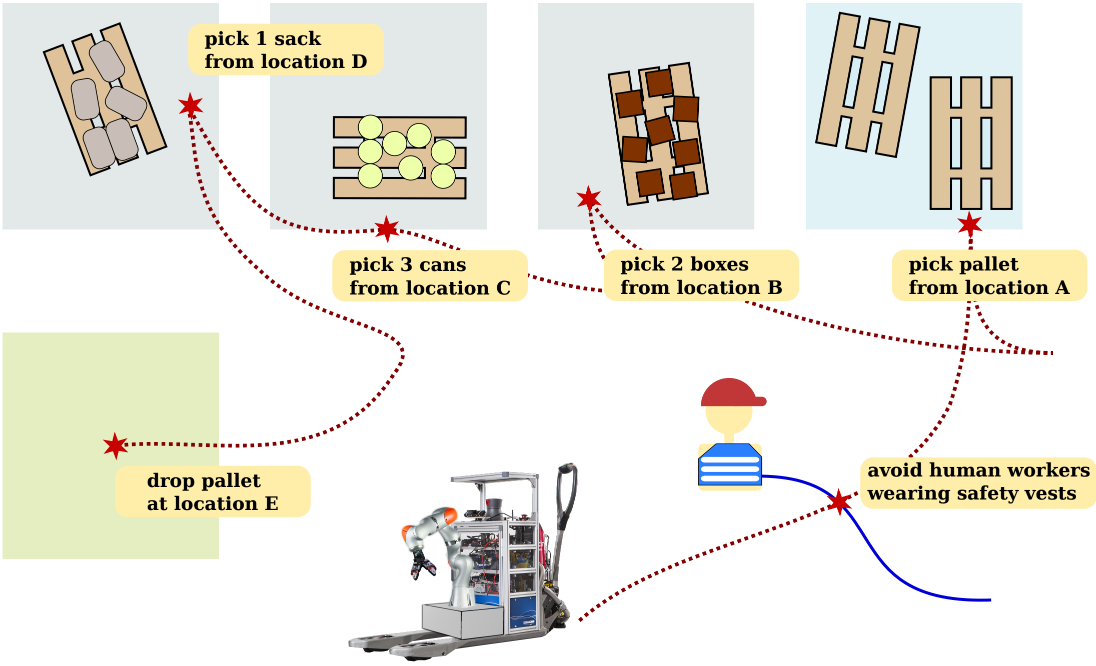

Figure 2: *APPLE scenario:* Shown is a sketch of the workflow - the platform picks up an empty pallet and visits different load zones to fill it with goods before delivering it to the target.

implementations developed during previous projects at AASS (see Section 3 for more details).

The key obstacle for many application scenarios is the autonomous grasping in uncertain real-world environments. Currently, despite of a large research effort, no commercially viable solution is available for this problem. State of the art autonomous grasping systems [12, 13, 2] commonly employ sampling based planners [14] to generate online reach-to-grasp motion plans for offline planned grasps which are stored in a database. During the execution phase, such approaches necessitate many futile motion planning attempts which often incurs significant time delays mainly due to the frequent collision checks which are necessary to avoid the robot coming in contact with itself or the environment.

For APPLE, we adopted a real-time reactive control approach for manipulator motion generation which allows to exploit redundancy, opposed to the commonly used sense-plan-act architectures which constrain all manipulator DoF. The main idea is to formulate a hierarchical set of tasks [15] such as “move end-effector on this plane” or “avoid joint limits” and to compute controls such that tasks of lower priorities are executed in the null-space of higher ranked tasks [16, 17, 18].

3 Approach and Realization

The software of the APPLE system consists of the following modules:

Autonomous Vehicle Navigation This module ensures that the AGV is capable to move autonomously and safely through the workspace environment. In order to achieve this task, we use components of a navigation system previously developed in the context of our KKS-funded Safe Autonomous Vehicles (SAUNA) project. We construct a 3D map of the static parts of the environment (using [6]) and use it to localize the vehicle in the presence of dynamic entities (using [8]). For motion planning and control of the non-holonomic AGV, we will our lattice planner [19] and a model-predictive tracking controller. The complete navigation system has been implemented, extensively tested and successfully integrated on the APPLE demonstrator, a detailed description can be found in [20].

Driving Path Visualization Information about the vehicle's driving path is visualized using an on-board projector. This is a first step for a solution for Human Robot Interaction (HRI) in industrial environments that will enable smoother collaboration between AGV's and human workers. The projector's output is generated using the GLUT 3D rendering framework. The perspective projection position and orientation is obtained from calibration combined with the localization estimates of the vehicle, thus a common reference frame is used. A green line shows the path of the truck where the origin of the vehicle is given as the center between the fixed front wheels. Also displayed is a white bounding area which is obtained by sweeping a footprint of the vehicle along the path.

People Detection As the envisioned mobile manipulation system will operate in environments shared with human workers, people detection and human safety are important issues. In APPLE we address the problem by using the RefleX system we recently developed [10]. RefleX is a camera-based on-board safety system for industrial vehicles and machinery for detection of human workers wearing reflective vests worn as per safety regulations. The system was designed with industrial safety standards in mind and is currently being tested as an industrial prototype.

Manipulator Motion Generation For reactive on-the-fly motion generation we formulate a stack of hierarchical tasks and use the recently developed method by Kanoun et al. [21], which allows to account for inequality tasks and solves a sequence of convex optimization problems at each time step to obtain appropriate joint velocity commands (the method also can be used to directly generate torque commands while accounting for the robot dynamics [22]).

Obstacle avoidance is also achieved on a control-level, by formulating tasks which maintain minimum distances between simple geometric primitives such as spheres, planes, points and capsules. We argue that for the considered application strict collision avoidance is neither necessary nor desired, since picking and manipulation inherently ne-

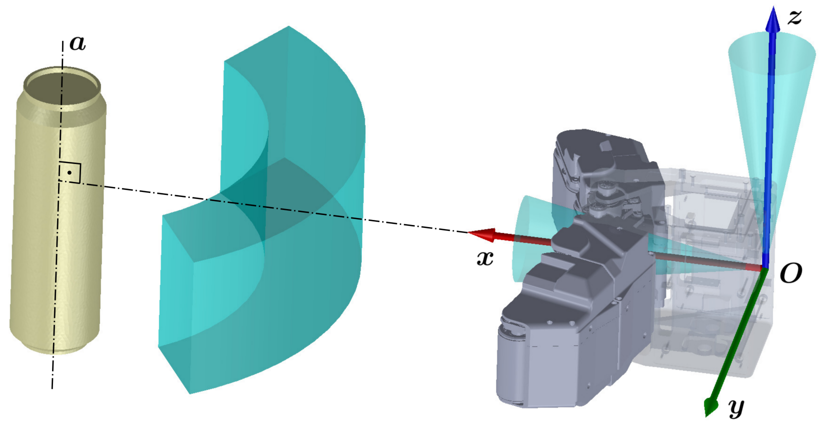

Figure 3: *Grasp interval:* Shown are exemplary grasp interval regions for a cylindrical object. A grasp can be successfully executed if the gripper's palm frame origin O is located anywhere within the cyan-colored cylinder shell segment and the gripper is properly oriented. The latter condition is ensured by keeping the palms z-axis in a cone which is aligned with the object axis a, as well as keeping the gripper's x-axis in a cone which is centered on the line connecting O with a. Positioning and opening angle of the cylindrical shell region depend on the pose of the object in the current scene and have to be determined by the perception module such that no collisions with adjacent objects/obstacles occur.

cessitates contact events between the robot and the environment. Also, in real-world applications where knowledge about the environment is available only in form of noisy sensor data, it might not be possible to avoid contacting the environment without being overly conservative. This makes the KUKA LBR iiwa with its compliant low-level control schemes and contact detection abilities an ideal platform for the tackled purpose and motion generation scheme. The relatively simple picking task in APPLE provides an ideal testbed in a real-world scenario.

Object Perception and Grasp Planning In order to detect target objects, we use an Asus Xtion Pro RGB-D camera, mounted on the wrist of the KUKA LBR iiwa. Pallet detection and picking is adopted from our previous work on the KKS SAUNA project, standard processing algorithms from the Point Cloud Library [23] are employed for target object detection. Instead of representing grasps as discrete gripper wrist poses and joint configurations, we use grasp interval regions as depicted in Fig. 3. These grasp intervals can easily be transcribed as target tasks for the manipulator motion control and allow for redundancy in the manipulator wrist positioning which eases reach-to-grasp acquisition. Grasp interval formulation depends on the specific target object and has to be verified experimentally. For now, we constrain ourselves to cylindrical objects as shown in Fig. 3. We then rely on the inherent capabilities of the grasping device and the compliance of the system for successful grasp execution as stated below.

Robust Grasp Execution For this component, we adopted the approach we developed in RobLog and leverage the capabilities of the Velvet Gripper, namely underactuation and conveyor belts on the finger pads in order to achieve robust grasping behavior.

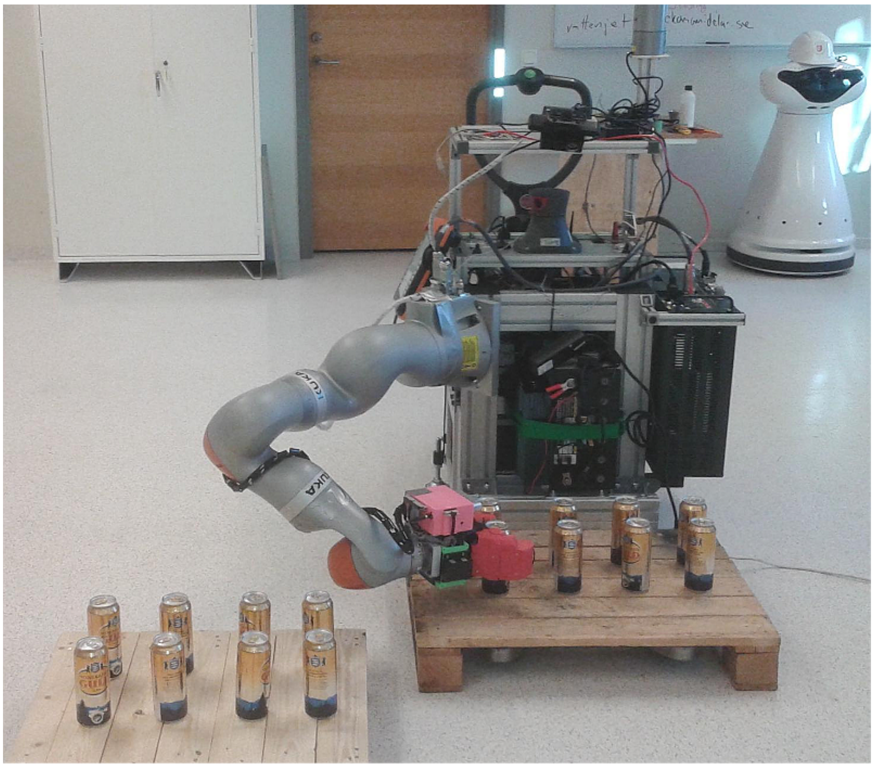

Figure 4: *Demo setup:* The robot loads beer onto a previously picked up pallet and subsequently transports it to a predefined target location.

Especially in cluttered scenes, a “pull-in” strategy has been shown to be especially effective to achieve stable grasps while starting from a relatively wide range of initial gripper poses with respect to the target object [2]. Here, the features of the grasping device are exploited to embrace the object in a firm envelope grasp by simultaneously squeezing it in a compliant fashion while actuating the belts inwards.

3.1 Demonstration Setup

Since the development time so far was very short, the demonstration for the KUKA Innovation Award is intended to only showcase the possibilities. From the full commissioning scenario depicted in Fig. 2, we selected the following elements (see Fig. 4) having in mind the resources on our side and potential space restrictions at the demonstration site: the robot picks up an empty pallet and moves to a loading area where a pallet with a loosely spaced matrix of cans is placed. Then, the manipulator transfers the cans to the carried pallet which subsequently is transported to a target location. Each of the previously described modules can also be demonstrated separately in case of further space limitations. The video attachment to this application can be found at `http://youtu.be/p8rja0_08io` and shows a fully autonomous preliminary version of the demo and highlights the major software components.

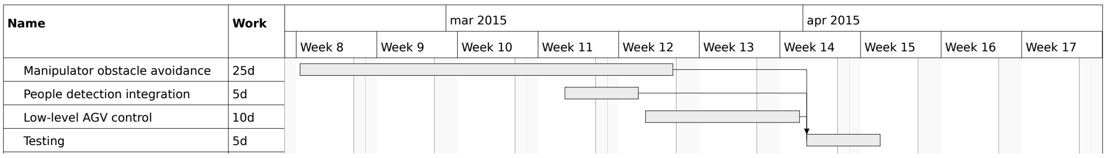

Figure 5: *Work plan:* Gantt chart illustrating the remaining project tasks.

3.2 Work Plan

As shown in the video attachment, the most of the aforementioned modules are fully integrated and tested on the APPLE platform. We intend to improve the collision avoidance behavior of the manipulator (currently only collision avoidance between spherical and planar geometries is enabled) by extending the possible geometries to Sphere Swept Volumes (SSV). Also, an agreement with our partner company Kollmorgen was reached who will improve the currently rather poor tracking behavior of the low-level AGV motion controller. Finally, we will integrate the RefleX camera system on the APPLE platform and allow for humans wearing reflective to be detected and avoided during AGV motion. The work plan for these remaining tasks is illustrated in Fig. 5.

3.3 Used hardware, libraries and resources

The software of the APPLE system uses the Robot Operating System (ROS) middleware to integrate the aforementioned software components. The software modules implementing autonomous navigation are part of our perception_oru suite[5] and are licensed under the FreeBSD license. We also use corresponding sensor drivers and vehicle controller interfaces, implemented in ROS. The low-level control of the AGV is performed by an on-board proprietary vehicle controller from Kollmorgen[6]. Solving the optimization problems for the manipulator motion control is done with an off-the-shelf solver [24], for future use we plan to use a more efficient tailored solution [25].

In terms of hardware (see Fig. 1), we employ a retrofitted Linde CitiTruck[7] as AGV. The utilized Velvet Fingers gripper is developed by the Centro E. Piaggio at Pisa University, Italy. For localization a Velodyne-32 HDL laser range finder[8] is used. Furthermore, we employ an Asus Xtion Pro RGB-D camera for object detection. An industrial prototype of the people detection system, comprising three cameras plus software implementation, exists at AASS and has already been evaluated in various industrial scenarios.

4 Results and Measures of Success

The overall system developed in APPLE can be considered at Technology Readiness Level (TRL) of 5: Component validation in relevant environment. The modules for

[5] `http://wiki.ros.org/perception_oru`
[6] `http://www.kollmorgen.com`
[7] `http://www.citi-truck.com`
[8] `http://velodynelidar.com/lidar/hdlproducts/hdl32e.aspx`

autonomous navigation and people detection have already been demonstrated in the context of project dissemination of KKS funded projects and can be considered to have attained TRL 6 (see `http://youtu.be/iEfl_C45HAo`[9]). The robust grasp execution module has been recently demonstrated as a component of the FP7 RobLog project (`http://youtu.be/VBTMtVC4IdA`). The two modules which were extensively developed for the purpose of APPLE (manipulator motion generation & object perception and grasp planning) are currently at TRL 5.

We verified the functionality of the whole system on a set of test runs in the described application scenario which is shown in the video attachment. One full test run (picking up an empty pallet, loading and pallet transport) takes approximately 4 minutes, of which the loading cycle (object perception and pick & place of a can) consumes roughly 2 minutes.

Our long term goal is to use the APPLE demonstrator as a research platform for optimal control-based robot motion generation. The task-prioritized control scheme used in the manipulator motion generation can be seen as a limit case of an optimal control problem, where controls are only optimized for a single time-step instead of over the full task execution time (or at least a limited preview horizon). We envision a holistic optimal control framework for the combined manipulator/AGV system to simultaneously decide where and how to move on the fly. Today, optimal control approaches in robotics have mainly been applied in simulation [26, 27]. The APPLE demonstrator provides an ideal test-bed to investigate the viability of this, conceptually very powerful, paradigm in intralogistics application scenarios.

5 Economic Analysis

Logistics and transportation has been identified as one of the key market domains in the Strategic Research Agenda of the EU robotics SPARC public-private partnership. Thus, applications which target specific step changes in TRL have been identified as key to the development of robotics research and innovation in Europe. A measure of the potential for development of the automated logistics sector is also given by the recently released annual report of the International Federation of Robotics (IFR)[10]. According to the IFR press release: *About 1,900 logistic systems were installed in 2013, 37% more than in 2012, accounting for 9% of the total sales of professional service robots. Thereof, about 1,300 automated guided vehicles in manufacturing environments are building up an increase of almost 70% compared to automated guided vehicles sales numbers in 2012. Despite the improvement of the data base, it is assumed that the actual number of newly deployed systems is far higher.* The report concludes that *Between 2014 and 2017, more than 10,200 logistic systems will be sold, thereof, about 9,200 automated guided vehicles.* Thus we conclude that the market potential for systems based on the APPLE project demonstrator is substantial.

[9] Please do not share this video as some results are still confidential!

[10] `http://www.worldrobotics.org/uploads/tx_zeifr/Executive_Summary_WR_2014_01.pdf`

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