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A Modular Robot System for Agricultural Applications

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Abstract

Agricultural tasks are manifold: Dependent on the crop, the environment and the desired plant maintenance operation, properties, such as modularity, robustness, compactness or user friendly interfaces, are advantageous for the automation using a robotic system. Therefore, several robotic manipulators have been designed and built for the requirements given by the EU-FP7 project CROPS[1] for multiple applications, including selective harvesting and precision spraying of high-value crops such as sweet-peppers, apples or grapes. Its mechanical design and communication structure will be presented in the first part of this paper. Compact integrated drive units including motor, brake, gear and motor drivers support the modular design of the manipulator. Thus, the developed system can be used in different kinematic configurations according to the special needs of each application.
The second part addresses the testing and evaluation concepts and tools in view of the challenges of the simultaneous development of the robot system within a large, spatially distributed project like CROPS. A setup for evaluation and validation of developed algorithms and functions in the laboratory as well as tools and concepts for simultaneous development of interfacing subsystems are shown. The manipulator can be controlled by an ROS interface in various operation modes. Hence, robot systems for three applications (sweet-pepper harvesting, apple harvesting, precision spraying) were implemented with full integration of the manipulator prototype.

Keywords: redundant manipulator, harvesting robot, manipulator interfaces, hard- and software architecture, experimental setup

1 Introduction

Although a large number of manipulative tasks already has been automated for industrial applications, many operations in agriculture are still done by human workers. Agricultural tasks without manipulative requirements, e.g. bulk harvesting of grapes (Pari & Pezzi, 2009) or uniform spraying of grapes (Stentz, Dima, Wellington, Herman, & Stager, 2002), have successfully been automated. However, there is still a lack in the field of plant maintenance operations such as harvesting of single crops or precision spraying of infected areas. An early overview of robotic manipulators for agriculture, quantitative requirements and applications can be found in (Sarig, 1993; Tillett, 1993). One major challenge compared to industry is the highly diverse and cluttered environment: Manipulators and sensors must be able to cope with various geometries of obstacles and targets. Detection and motion planning algorithms have to generate new manipulator trajectories adapted to every target in a short time horizon. Due to short and intense seasonal harvesting periods, a multipurpose system for different crops and applications would be desirable.

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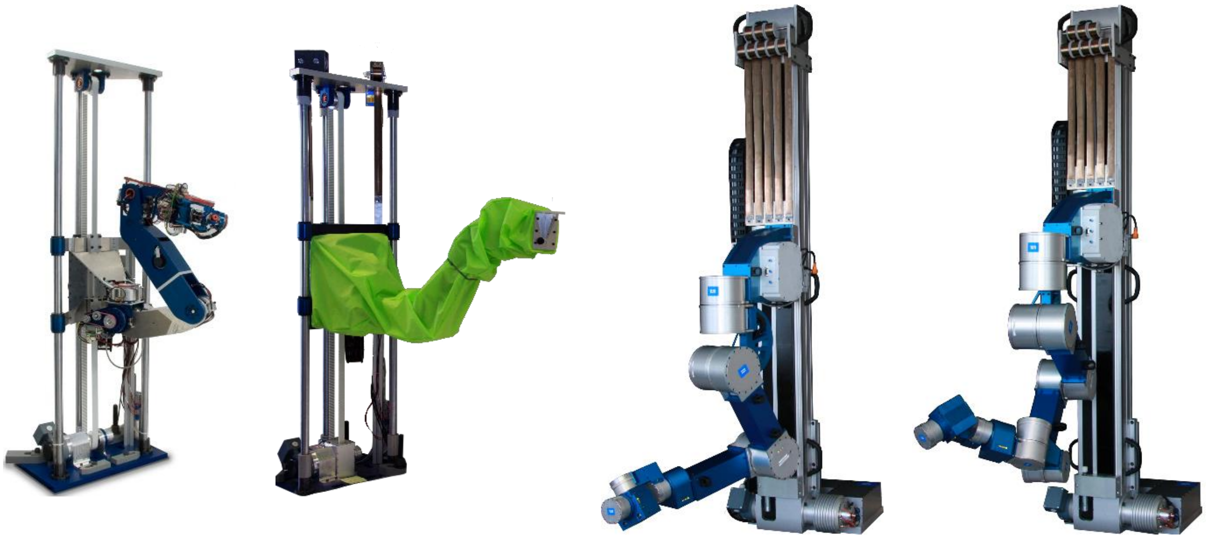
[1] EU- project CROPS (Clever Robots for Crops), Grant Agreement No. 246252, http://www.crops-robots.eu.

Several groups made use of standard industrial manipulators (usually 6 degrees of freedom (DOF)) while increasing the workspace by mounting them on linear axes and/or mobile platforms. Examples can be found for apple harvesting (Baeten, Donné, Boedrij, Beckers, & Claesen, 2008), cucumbers (van Henten et al., 2002) and palm fruits (Aljanobi, Al-hamed, & Al-Suhaibani, 2010). However, standard industrial manipulators are heavy, fixed in their dimensions and therefore not adjustable to the needs of different crops or growing periods. Thus, custom manipulator systems for specific tasks have been designed such as for orange (Muscato, Prestifilippo, Abbate, & Rizzuto, 2005) and kiwi picking (Scarfe, Flemmer, Bakker, & Flemmer, 2009) or sweet-pepper harvesting (Kitamura & Oka, 2005). A multipurpose system for grapes has been designed by Monta, Kondo, & Shibano (1995).

Within the EU-project CROPS, a modular, multipurpose robot system is being developed which is usable for various automated applications (selective harvesting of sweet-pepper, apples and grapes, precision spraying of grapes). While other partners within the consortium develop suitable sensor systems and image processing algorithms for fruit, obstacle and disease detection, our institute designs and builds the manipulator systems. In course of the project, two manipulator prototype generations have been designed and built from scratch, which are presented in the following paper.

In Sec.2, we describe the manipulator design, which is derived from given task requirements. We present its kinematics, its hardware and communication system. Sec.3 deals with the integration methods and tools applied for the manipulator within the project. A short overview of the considered applications is given in Sec.4.

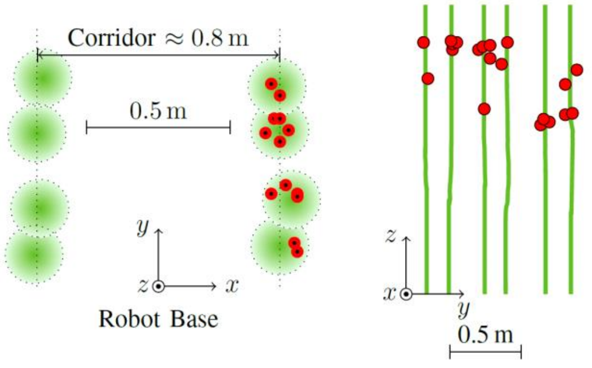


(a) Gen. 1 – 9 DOF (b) Gen. 1 – 6 DOF (c) Gen. 2 – 7 DOF (d) Gen. 2 – 9 DOF

Figure 1 Agricultural Manipulator Prototype Generations. Generation 1 in 9 DOF configuration (a) and 6 DOF configuration with protection cover for precision spraying (b). Generation 2 in 7 DOF configuration (c) and 9 DOF (d) configuration.

2 Manipulator Design

For positioning the end-effectors and sensors, a manipulator system is needed which is able to cope with the varying requirements of the investigated applications. The first generation manipulator prototype, developed and built at our institute, was ready in the beginning of 2012 and a second, completely redesigned and improved generation has been delivered to the partners at beginning of 2014 (see Figure 1). In the following section, requirements for a multipurpose manipulator system are discussed and the kinematic, hardware, communication and user interface design is presented. In course of this, we focus on the second manipulator generation which shows a heavily improved design compared to the first generation. Details on the first generation can be found in (Baur, Pfaff, Ulbrich, & Villgrattner, 2012).



(a) Topview (b) Sideview

Figure 2 Topview and sideview of a greenhouse corridor for sweet-pepper cultivation based on real measurements. The plants are represented by the shaded green circles while fruits are drawn in red.

2.1 Task Description and Requirements

The considered applications within the CROPS project are

- Selective harvesting of sweet-pepper
- Selective harvesting of apples
- Selective harvesting of grapes
- Precision spraying of grapes

The requirements vary for each application in terms of reachable workspace and dexterity. We consider sweet-pepper harvesting to be the most challenging task due to the workspace geometries and the positioning requirements. Hence, we present exemplarily this harvesting scenario in detail.

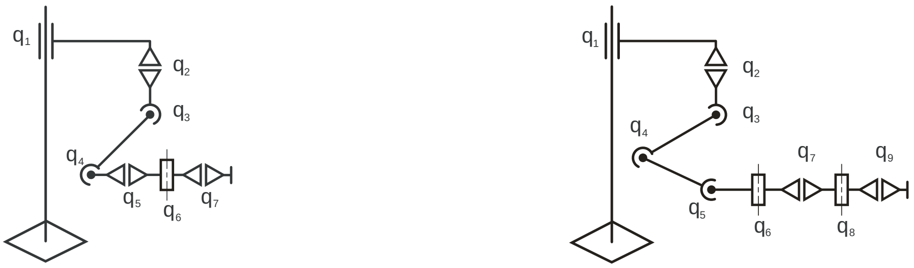
In European regions, sweet-pepper fruits are usually cultivated in greenhouses, where the climate is mostly humid. Depending on the plant growth, fruits have to be harvested in a height from $0.3m$ up to $4m$ relative to the floor. They are often occluded by leaves, stems or other fruits. The corridors between the plant rows are narrow ($\approx 0.4 - 0.8m$). Furthermore, an average harvesting time of $6s$ per fruit is desired. An example of a scenario based on real plant data is illustrated in Figure 2. Detailed information on the harvesting scenario including a statistical evaluation of fruit positions and dimensions can be found in (Baur, Schuetz, Pfaff, Buschmann, & Ulbrich, 2014).

2.2 Kinematics

For all application scenarios, the manipulator is mounted on a mobile platform, which is able to move along the corridors in greenhouses or orchards (y *–Axis,* Figure 2). Although most of the fruits e.g. in the sweet-pepper scenario are hanging within a range of about $1m$ in vertical direction, a wider range ($\approx 1.5m$) has to be covered due to several outliers. Therefore we decided to use a prismatic joint as q_1 , as it is often reported in literature (refer to Sec.1).

Depending on the end-effector type, varying demands are made on dexterity of the manipulator. The hardware design of the generation 2 prototype promotes multiple kinematic configurations due to its modular concept. Up to now, two optimized configurations with 7 degrees-of freedom (DOF) and 9 DOF, respectively, have been realized and are shown in Figure 3. While the last 3 DOF (“wrist”) remain in the same configuration, q_5 and $q_6$of the 9 DOF configuration are replaced by a rigid link to obtain the 7 DOF configuration. The real manipulator in both configurations is shown in Figure 1.

The workspace W may be chosen arbitrarily. A common choice is the position $(x, y, z)^T$ and orientation $(\alpha, \beta, \gamma)^T$ in Euler XYZ angles.



(a) 7 DOF configuration *(b) 9 DOF configuration*

Figure 3 Kinematic Configurations of Manipulator Prototype Generation 2. See Figure 1, c/d for photos of the real manipulator prototype.

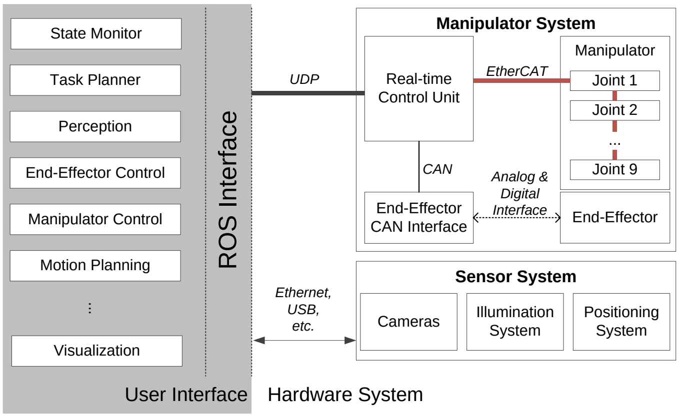


Figure 4 Communication and interface architecture of the robot system with the manipulator prototype generation 2.

2.3 Hardware

While the prismatic joint is realized with a Festo linear bearing driven by a high-torque brushless DC motor, the rotational joints have a similar structure but vary in size. Each contains a HarmonicDrive gear, high-torque BLDC motor, absolute encoder, brake and an Elmo Gold motor driver, sealed in a waterproof housing. For details on the drive modules refer to (Pfaff, Baur, Schuetz, Buschmann, & Ulbrich, 2014). The modules are connected with rigid links and easily plugged in with one connector board carrying all power and communication electronics. Hence, no outer cabling for the manipulator itself is needed. Constant-force springs are applied on the prismatic joint for gravity compensation of the manipulator arm.

2.4 Communication and Control

The manipulator drive units are connected in a line via the real-time bus system *EtherCAT* to the real-time control unit (RCU) which is programmed with MathWorks *XPCTarget* and serves as the EtherCAT master device. Each motor driver transmits and receives position, velocity, active current and status at a sampling rate of $1ms$. The joints are controlled by a decentralized control scheme implemented on the motor drivers on position or velocity level.
On the RCU, the inverse kinematics with self-collision avoidance as well as the workspace path planning is calculated in real-time (for details on the algorithms refer to (Baur, Schuetz, Pfaff, Buschmann, & Ulbrich, 2014)).
The RCU also provides a CAN interface, where the interface board (Atmel *AT90CAN*) for the end-effectors is connected to. The interface board converts the CAN messages to digital and/or analog signals for the attached end-effector and transmits status messages backwards. The RCU is connected via UDP to the user interface PC, where a ROS (Quigley et al., 2009) interface node provides several options for controlling the manipulator (refer to Sec.3.2). The scheme is given in Figure 4.

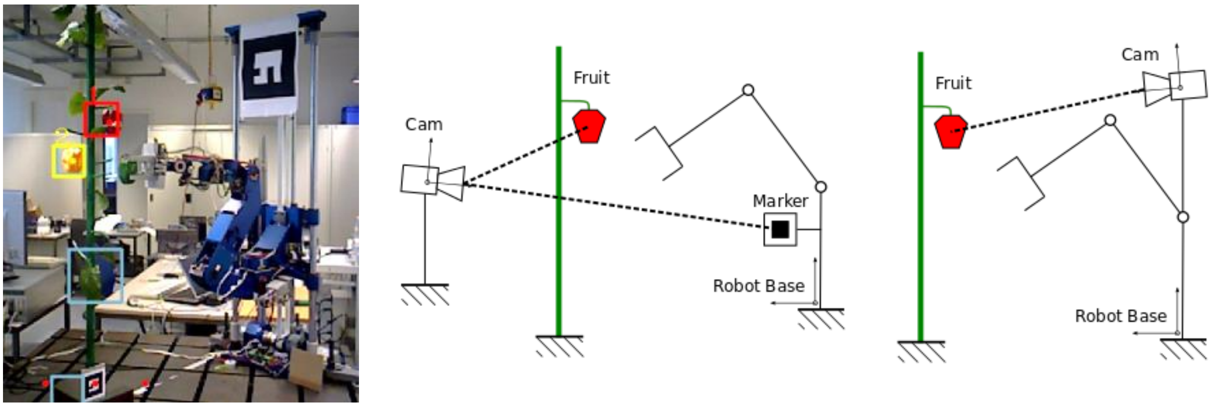
3 Manipulator Testing and Integration

Since the development and testing of the components within the EU project CROPS happens in parallel at several institutes and companies at different locations, interfaces have to be well defined and suitable testbeds are needed. In this section we present the manipulator laboratory testbed and the interfaces, which can be used by other modules such as task managers or path planners.

Figure 5 Laboratory testbed at TUM for harvesting sweet-pepper and apples. The fruits are hinged with magnets on stems, which hang from the top and can be adjusted in the $x - y$ plane.

3.1 An Advanced Laboratory Testbed with RGB-D Fruit Detection

For testing and evaluating different path planning, collision avoidance, optimization, etc. algorithms, we designed a testbed in laboratory mimicking the sweet-pepper and apple harvesting scenario (Figure 5). Fruits can be detected and localized by a RGB-D camera device (ASUS *XTion*). The fruits are first detected in the 2D RGB image by an cascade boosting machine learning algorithm using Haar features and several filters (Figure 6a). The localization in the camera frame is done using the depth information and the calibration from RGB and depth data. Since the fruit position is required w.r.t. the robot base, we firstly used an arbitrary camera position. The camera detects a marker on the robot and the fruit in the same frame, thus, the fruit position (w.r.t. the robot base) can be estimated (Figure 6b). This setup was very flexible, but due to the length of the kinematic chain *(fruit-camera-robot)*, it occurred that the position error was too high for successful operation in practice. Hence, we decided to mount the camera directly on top of the manipulator (Figure 6c). First experiments were promising, while testing and evaluation is still ongoing.



(a) Fruit localization in laboratory from camera view

(b) Concept: arbitrary positioning of the camera device

(c) Camera device mounted on manipulator

Figure 6 Laboratory setups for fruit localization by ASUS XTion RGB-D camera device

3.2 Interfaces and Simulation

The ROS interface node on the user PC (refer to Sec.2.4) provides several interfaces for controlling the manipulator arm. An overview is given in Table 1. The commands are either implemented as preemptable tasks or messages (in the robotic middleware ROS this corresponds to *Actions* and *Messages*).
To enable the testing and integration process for all partners of their subsystems with the simulated manipulator, a Linux based simulation tool of the RCU has been developed by our group. In combination with the ROS manipulator interface UDP node, all presented interfaces are available for the user.

Table 1 Overview of the Manipulator User Interfaces

Interface	Target Variable	Type
Point-to-point end-effector movement to a desired goal pose on a straight line	$(x, y, z, \alpha, \beta, \gamma)^T$	Action
Point-to-point end-effector movement to a desired goal position on a heuristic path accounting for the stem and fruit position (Baur et al., 2014)	$(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})^T$	Action
Online joint velocity control	$(\dot{\boldsymbol{q}}_{\boldsymbol{1}}, \dot{\boldsymbol{q}}_{\boldsymbol{2}}, \dots, \dot{\boldsymbol{q}}_{\boldsymbol{9}})^T$	Message
Online end-effector velocity control (Workspace)	$\left(\dot{\boldsymbol{x}}, \dot{\boldsymbol{y}}, \dot{\boldsymbol{z}}, \dot{\alpha}, \dot{\beta}, \dot{\gamma}\right)^T$	Message
Offline joint trajectories	$t_0 \quad (q_1, q_2, \dots, q_9)^T$ $t_1 \quad (q_1, q_2, \dots, q_9)^T$ $\dots \quad \dots$	Message

(a) Sweet-Pepper (b) Spraying (c) Apples

Figure 7 Manipulator Prototype (Generation 1) integrated by the applications sweet-pepper harvesting, aplpe harvesting and precision spraying within the EU project CROPS.

(a) Manipulator on platform in a greenhouse for sweet-pepper cultivation. Experiments and system integration realized by *Wageningen University and Research Center*. Gripper by *FESTO*.
(b) Manipulator in 6 DOF configuration with protection cover on a platform for precision spraying of grapes. Experiments and system integration realized *Università degli Studi di Milano*. Sprayer by *University of Ljubljana*. Picture by Uni Milano.
(c) Manipulator mounted on a tractor (CNH) in an orchard for apple harvesting. Experiments and system integration realized by *MeBios group* at *KU Leuven*. Picture by KU Leuven.

4 Applications

The manipulator prototypes we presented in this paper have been successfully used for several agricultural applications within the EU project CROPS. The testing, evaluation, integration as well as optimization process is still ongoing in field tests. Figure 7 gives an overview of the currently implemented applications.
The selective harvesting of sweet-pepper fruits in greenhouses is led by Wageningen University and Research Center, Applied Plant Research (WUR). The manipulator is mounted on a mobile platform and guided on rails between the rows. The platform is equipped with the sensor system for fruit detection. The manipulator prototype generation 2 is currently being tested with an adaptive jaws gripper with a scissor like cutting device from FESTO and an end-effector for fruit removal developed by WUR. More details on the sweet-pepper harvesting application can be found in (Hemming et al., 2014).

Selective harvesting of apples in orchards is conducted by KU Leuven (Nguyen, Kayacan, De Baerdemaeker, & Saeys, 2013). The manipulator system is mounted on a tractor by CNH and equipped by a membrane jaws gripper by FESTO.

Aiming for reducing the amount of pesticides, an autonomous disease detection system for grapes transmits the coordinates of infected areas to the manipulator, which positions a high flow rate spraying end-effector for precision spraying. Since the requirements on dexterity were lower than for the harvesting applications, the manipulator has been used in the 6 DOF configuration. This application is headed by the Università degli Studi di Milano (UniMi) and the end-effector is developed by the University of Ljubljana (UniLj). For more information refer to (Oberti et al., 2014).

5 Conclusions

We have developed and built two manipulator prototype generations from scratch at our institute including the mechanical, electrical and software components. As it is shown at the different applications, the manipulator system is well suited for a multipurpose use due to its modular hardware and software design. Further improvements on the manipulator system regarding the motion planning algorithms are currently under investigation (Baur, Schuetz, Pfaff, Buschmann, & Ulbrich, 2014; Schuetz, Buschmann, Baur, Pfaff, & Ulbrich, 2014) and will be in the focus of our upcoming research.

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