International Conference of Agricultural Engineering
AgEng 2014 Zurich 6–10 July

Ref: C0345

Design of Drive Units for Agricultural Robots

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Abstract

The demand for high quality food is rising while the supply of labor is decreasing at the same time. In order to meet this challenge, it is necessary to further improve the production of food. Virtually all field crops are planted, cultivated and harvested with specialized machinery. Harvesting and pruning individual plants and fruits in demanding environments such as greenhouses by autonomous robot systems, however, is not yet state of the art. Automating these tasks requires more complex and flexible machines than those currently available, i.e., specialized agricultural robots.

Different tasks, varying environmental conditions and the characteristics of the plants call for a modular design approach. Although it will not be possible to deal with all variations, a reconfigurable robot can be used for several tasks and plants. Hence, more demanding actions like harvesting require more dexterous manipulation to be able to reach all fruits, while pruning or spraying could be done with less degrees-of-freedom.

This paper describes modules that can be used to build robots adjusted to particular functions. We built different sized modules with varying output power. Even though the size is changed, the basic design and components remain the same. Thus, the effort for development and construction can be minimized. To deal with the environmental conditions, the hardware, like motor and gear, as well as the electronics (motor controller or encoders), are placed inside a closed housing. We present the general design and construction of the modules in detail. The alignment and type of the components inside the unit will be shown as well as the mechanical and electrical interfaces for a simple assembling of the joints with the connecting elements. We compare the different sizes as well as commercially available drive modules with the help of the respective performance characteristics.

Eight modules of different sizes are used for the second generation of a harvesting and spraying robot developed as a part of the EU-Project CROPS[1]. Within the project, the manipulator is being tested for different applications, for example in greenhouses for harvesting of sweet peppers.

As a result, we will show the manufactured and assembled units as well as an example of two joints connected to each other using a coupling component. We will also present measurements taken on a test bed, which has been developed to evaluate the performance of different types of modules.

Keywords: Modular robotics, Robotic systems, Harvesting robots, Automation, Design and construction

[1] CROPS: Intelligent sensing and manipulation for sustainable production and harvesting of high-value crops - clever robots for crops (EU-project, www.crops-robots.eu)

1 Introduction

In the past decades, there has been put a lot of effort in the improvement of the cultivation and harvesting of plants and fruits. While bulk harvesting on fields is already highly automated (Pari & Pezzi, 2009), there are still a lot of fruits which have to be harvested by human workers. Especially high value crops in unstructured and cluttered environments require specialized robotic systems. There are manifold examples for harvesting robots like for asparagus or kiwifruits (Irie, Taguchi, Horie, & Ishimatsu, 2009; Scarfe, Flemmer, Bakker, & Flemmer, 2009).
In order to improve the efficiency of such robots, it is desirable, that they are able to harvest not only one specific fruit, but also different fruits under varying environmental conditions. For that reason, a modular and multipurpose robotic system is advantageous. Bryngelson & Tosunoglu (1994) describe a modular robot with 7 degrees of freedom (DOF), while Houxiang Zhang, Gonzalez-Gomez, Zhizhu Me, Sheng Cheng, & Jianwei Zhang (2008) present a robot module, that can be assembled in various configurations.
Even if the fields of application vary a lot, the basic structure of modular manipulators is more or less the same. The joints consist of powered drive units, which are connected to each other or via link segments. For the design of such drive units, two basic approaches exist: Flexible drives, which are due to their compliance well suited for applications with human interaction, but are more difficult to control, e.g. (Dong Hoon Cha et al., 2012; Pratt & Williamson, 1995). Alternatively, stiff drive units, which are very accurate and easier to handle, but require more weight to achieve the desired stiffness, e.g. (Lohmeier, Buschmann, Ulbrich, & Pfeiffer, 2006; Young-Jin Lee, Min-Kyu Park, & Seok-Jo Go, 2010).
Our aim is to develop drive modules that match the requirements that arise from the different tasks of spraying and harvesting in greenhouses and fields and are suitable for assembling a harvesting manipulator.
In Section 2, the process of the design and construction is described including the requirements, the concept and the final design. The results, containing the hardware as well as measurements of the drive units, are shown in Section 3.

2 Design

In this Section, we describe the development of the drive units. The requirements therefore are based on the needs that arise from the picking process of various fruits as well as from the environmental conditions in greenhouses and fields. Trying to cope with all these requirements we have developed a basic concept, which can be applied to different sizes of units. Finally we describe the design including the diverse components.

2.1 Requirements

A natural environment is much more complex than the common application area of robots in industrial automation. Leafs, branches and fruits interact with the manipulator. The drive units should have a closed housing to avoid damage by outer cabling, tubes or other components, that are endangered to get stuck. A closed and particularly sealed housing is also needed because of dust, humidity and rain, which could lead to serious damage on the drives.
A multipurpose manipulator concept has to be able to carry different kinds of end-effectors and fruits in a dynamic motion. To determine the resulting forces and torques in each joint, dynamics simulations on the basis of a 9 DOF manipulator with a load of 4kg and a motion time between $2s$ and $4s$ have been performed (Baur, Pfaff, Schuetz, & Ulbrich, 2013). Exemplarily, the torques of joint 3 for five different harvesting motions with $3.5s$ are shown in Figure 1 whereas in Figure 2 the resulting torques of the joints 7, 8 and 9 are depicted for one particular motion. The drive units were dimensioned based on these results

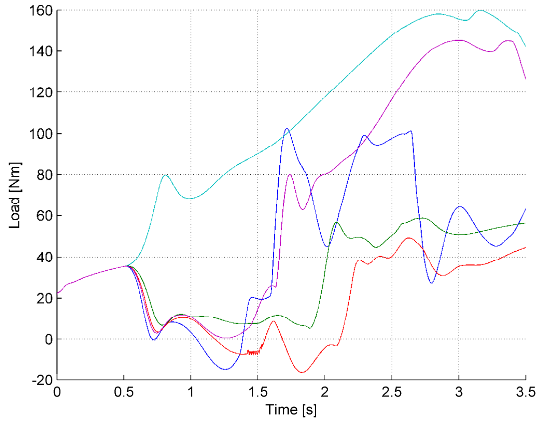

Figure 1: Dynamics simulation of joint 3 for five different harvesting motions

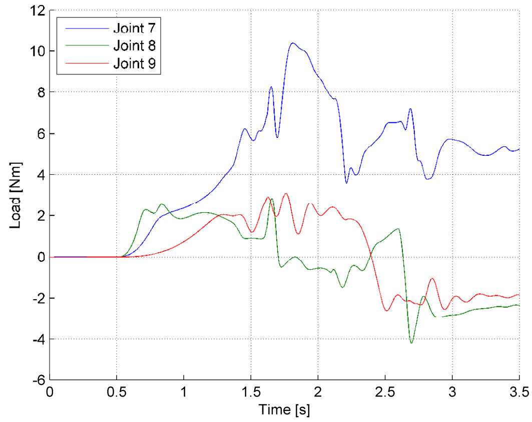

Figure 2: Dynamics simulation of joint 7, 8 and 9 for a harvesting motion

To simplify the usage of the arm it should always be ready to use without any indexing sequences. The reconfiguration of the manipulator has to be easy and without a lot of unplugging of cables.
For reasons of safety, each drive unit has to have a failsafe system to be able to stop in any case of error or emergency (e.g. power blackout, error in control unit, unexpected obstacles) for avoiding damage to the environment or the manipulator.

2.2 Concept

The concept has to fulfill the requirements collected in Section 2.1, but it also has to be easily applicable for different sizes of drive units, so that the effort on construction is minimized. All components to run the drive are desired to be placed inside one unit. To further reduce the time of development all main parts are intended to be purchased. However, by using frameless components, where available, we are able to design the housing according to our needs.
Based on the manipulator configuration, challenging trajectories might require a wide angle of rotation of single drive units. Therefore, it is desirable to permit a rotation angle of ±180°. As described in Section 1 there are two principle ways to design the housing of a drive unit. We decided to build stiff modules instead of flexible to decrease the development time. For that reason, the bearing of the output side is made of two angular ball bearings in an o-alignment, so that forces and torques are best possible handled.
The housing of the drive units is sealed. The input and output connections, though, are sealed not until the particular links are connected. For a fast reconfiguration of a manipulator, the assembly of drives and links has to be as easy as possible. To achieve this, one single board with connectors for power and signals is used. The mechanical connection is done with screws and aligning bolts.
The connection of the power electronics of each device has to offer a high bandwidth to enable a centralized control scheme. To guide the necessary cables for signal and power inside the units from one to another joint the main parts like motor, gear and absolute sensor have a through hole. An additional hollow shaft is used to connect the absolute encoder to the output side.
An incremental encoder is used for the motor commutation and positioning. It works with the cogging of a tooth wheel fastened on the motor shaft. Furthermore, this tooth wheel is used to link a safety brake to the motor shaft, which is engaged in case of a power loss.

2.3 Design

The dynamics simulations mentioned in Section 2.1 form the background of the construction. Based on these, three different sizes of modules (big, medium and small), using the concept

described, are developed. In addition to the size of the units, the reduction ratio of the gears can be varied according to the particular demands.
We achieved high torques and high speeds on the output side by using a combination of a BLDC high torque motor from TQ Systems with a reduction gear from HamonicDrive. The alignment can be seen in Figure 3. Besides the good performance of the components, they have big through holes, which are necessary for the design with a hollow shaft. The rotation of the motor shaft is measured with a magneto resistive encoder from Sensitec. The encoder uses the partitions of a tooth wheel to determine the exact position. Moreover, the tooth wheel is used to couple a safety brake from Kendrion to the motor shaft. The absolute encoder from Netzer is mounted on the input side. It is connected to the hollow shaft that is fixed to the output side and is thereby able to determine the exact absolute position of the drive unit.

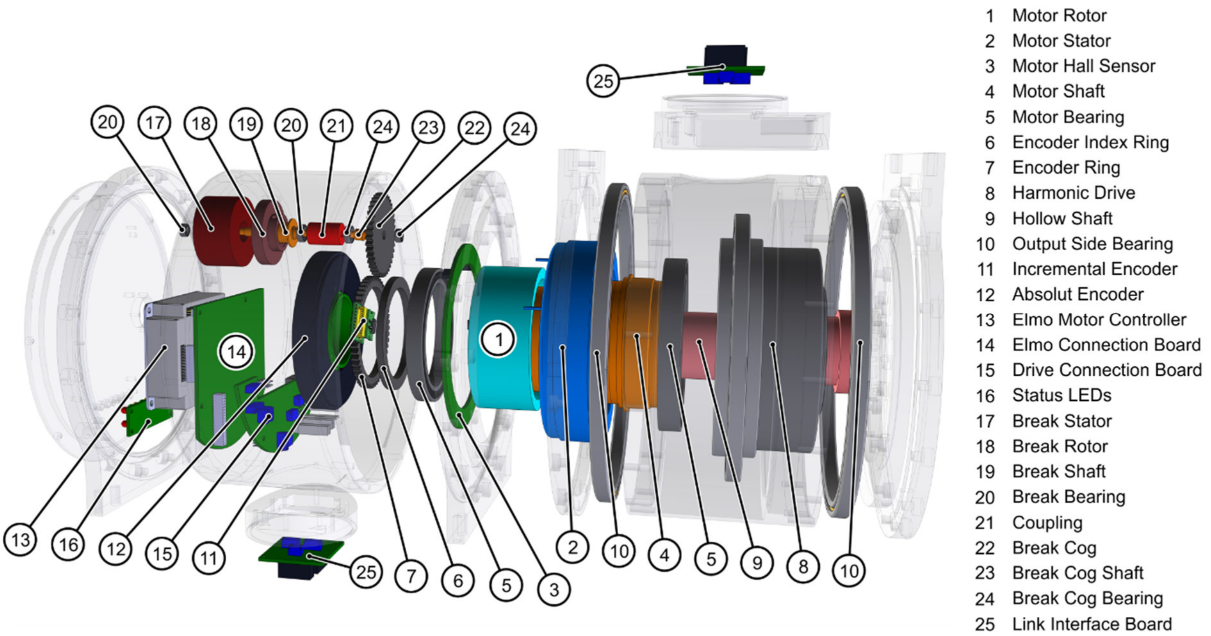

Figure 3: Exploded view of a the big drive unit

For the low level controlling we use power electronics from Elmo Motion Control. The communication interface between the joints and motor controllers, respectively, is based on the Ethercat protocol. It allows a high bandwidth and is therefore well suited for advanced real-time controlling architectures. The controller is mounted on a cover plate, which can be removed for the purpose of maintenance. Furthermore, there is a USB connector for a direct link to the power electronics as well as LEDs to display the status of the joint.
To allow an easy demounting of the cover, we designed a circuit board for the motor controller, which is separated in two parts but can be connected via socket outlet and plug. One board is fixed on the motor controller and is equipped with the necessary electronic components. The other board is attached to the housing and provides the connectors for the encoders, the motor as well as the link interface boards. Because of this separation, the cover plate with the motor controller can simply be pulled out.
The interfaces, where links can be mounted, consist of a mechanical and electrical component. Aligning pins are used for a stable and accurate connection. They also simplify the assembly and make sure, that the pins of the interface board meet with the corresponding sockets on the link.
The housing is made of aluminum. To accomplish a waterproof design, all contact surfaces are sealed with gasket material. The covers and the interfaces, which have to be demounted more often, are featured with O-rings.

2.4 Test Setup

A test bench was built to measure and verify the characteristics of the drive units. For a detailed description, refer to (Baur et al., 2014). With this test bench, the friction and the stiffness of different joints can be evaluated. To determine the friction T_f, the motor torque T_m times the gear ratio i is compared to the torque measured on the test bench T_b. The motor torque is calculated with the torque constant and the effective current I.

$$T_m = k_m I \tag{2-1}$$
$$T_f = T_m i - T_b \tag{2-2}$$

Accordingly, the stiffness of the setup k_s is identified by comparing the motor encoder φ_m with the test bench encoder φ_b. The stiffness of the drive k_d unit results from (2-5) with the stiffness of the test bed k_b. The tests can be performed with adjustable speeds and loads.

$$\Delta\varphi = \varphi_m i - \varphi_b \tag{2-3}$$
$$k_s = \frac{\Delta\varphi}{T_b} \tag{2-4}$$
$$\frac{1}{k_d} = \frac{1}{k_s} - \frac{1}{k_b} \tag{2-5}$$

3 Results

As results, we present the developed hardware as well as measurements of one drive unit, which display the friction and stiffness at different speeds and loads.

3.1 Hardware

In this Section, we present three sizes of drive units we developed. Figure 4 shows a big and medium unit as well as a link designed to connect these two modules. The mechanical and electrical interfaces of the input and output sides are depicted.

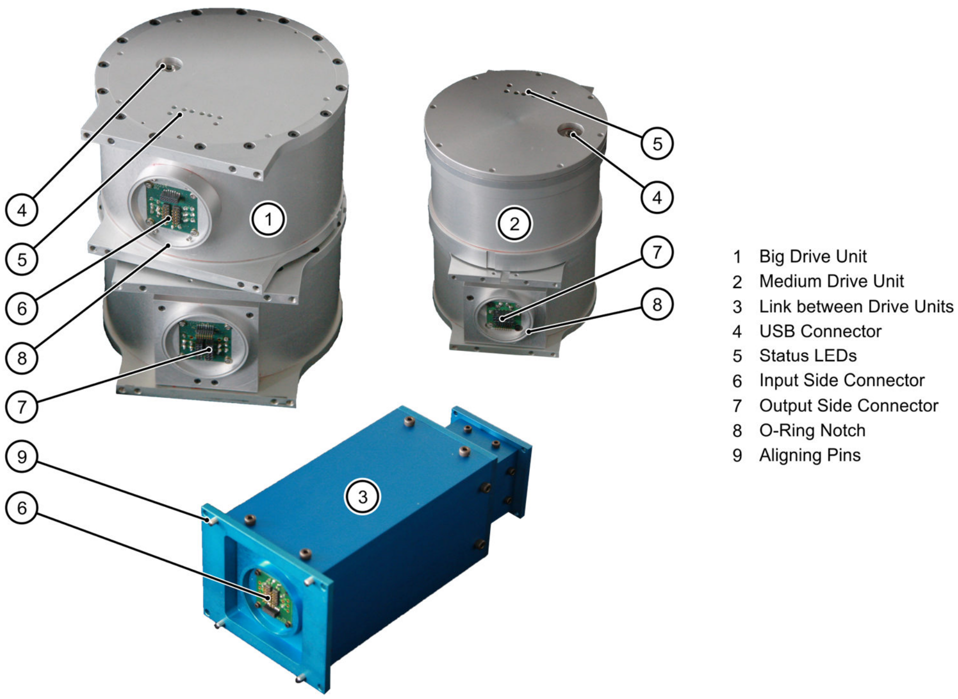

Figure 4: Big and medium drive unit with corresponding Link

Figure 5 shows an assembly of three small drive units, which are configured as a kind of wrist. The concept of the small units is still the same, but the implementation of the particular input side housings is adapted to the narrow space available. To gain a compact design the two units on the left side have a combined housing. They can be separated from the last joint at an additional interface.

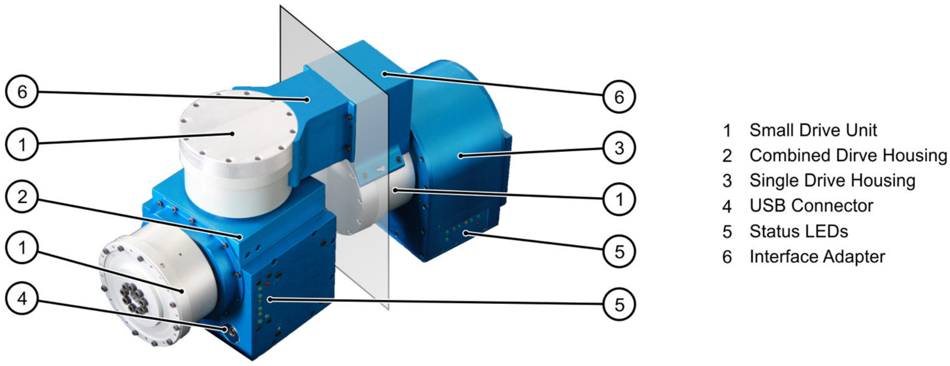

Figure 5: Small drive units in wrist assembly

Every possible configuration of unit and gear is shown in Table 1. The configurations, we built and used in the manipulator, are depicted as bold. All further combinations can easily be achieved by changing the particular gears, if needed. To compare the developed drive units with commercially available ones, we added the SCHUNK modules PRL 60 -120 to the listing. The outer dimensions of the PRL are slightly smaller and the torques are more or less comparable. However, there are two criteria, which were crucial for the new development. First and most important, the Schunk drives are too slow to be used in a harvesting robot. And second, they use a low bandwidth CAN Bus, which might prevent an enhanced real time controlling.

Table 1: Overview of drive unit configurations

Size	Reduction ratio	Max. speed [rpm]	Torque [Nm] Nominal	Torque [Nm] Max.	Weight [kg]	Diameter [mm]	Length [mm]
Big	**50**	**60**	**71,5**	**216**	4,293	146	175
	80	37,5	114,4	304			
	100	**30**	**143**	**333**			
	120	25	172	353			
	160	19	216	372			
Medium	50	100	14	39	1,806	104,5	128
	100	**50**	**28**	**57**			
	160	31	34	64			
Small	50	170	4,8	12	~0,8*	71-115*	110-130*
	100	**85**	**7,7**	**19**			
PRL 60	300	8,4	4,5	9,6	1,0	75	102
PRL 80	552	4,2	30,7	41,4	1,2	89	112,5
PRL 120	596	4,2	216	372	3,6	132	156

*Weight and dimensions depend on configuration (refer to Figure 5)

3.2 Measurements

The torsion of a big drive unit with a reduction ratio of $i = 50$ in the test bench setup is shown in Figure 6. The measurement is done at a motor speed of $10\,rpm$ and an increasing load of $0 - 40\,Nm$. To calculate the torsional stiffness of the joint, the stiffness of the test bench has to be subtracted.

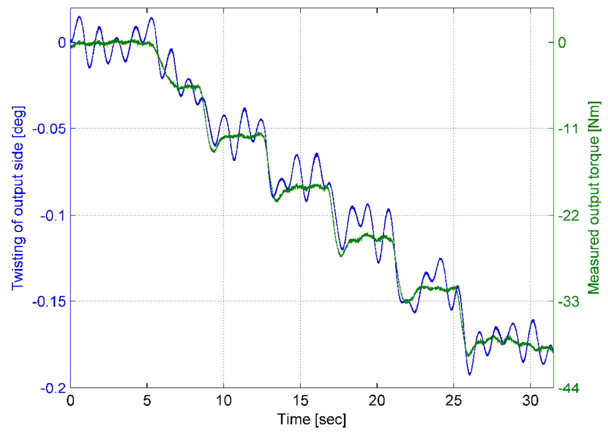

Figure 6: Comparision between measured output torque and twisting of the drive unit (measured with test bench encoder)

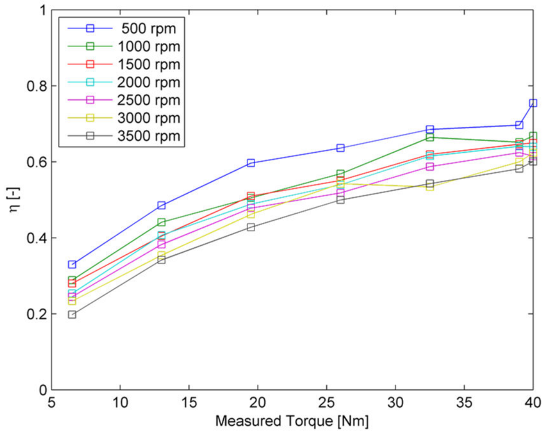

Figure 7: Efficiency measurement for different speeds

Figure 7 illustrates the efficiency η of a big drive unit with a CPL-32-50 HARMONICDRIVE gear at different motor speeds.

$$\eta = \frac{T_b}{T_m} \tag{3-1}$$

4 Conclusions

Eight of the developed drive units are used in the 9 DOF harvesting robot shown in Figure 8a (Schuetz, Pfaff, Baur, Buschmann, & Ulbrich, 2014). Because of the interfaces of every module the configuration can easily be changed to a, for example, 7 DOF configuration (Figure 8b). The performance of the overall arm meets our expectations and allows a fast harvesting of fruits, which is currently confirmed in tests in greenhouses (Hemming et al., 2014).

(a) 9 DOF (b) 7 DOF

Figure 8: Manipulator prototype generation 2 (2014)

To further increase the performance and flexibility, it might be useful to build another size of drives, which could close the gap between the big and medium size. Since the units are still prototypes, in prospective, the weight and dimensions can be further reduced, while the stiffness can be increased.

5 Acknowledgement

This research is co-funded by the European Union (CROPS GA no 246252). The authors would like to thank G. Mayr, S. Gerer and G. König for their technical support and contributions to the electrical and mechanical design. Furthermore we thank our partners within the CROPS consortium WUR, KU Leuven, UniMi and UniLj for their contribution at system integration and testing.

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