Proceedings of the OAGM&ARW Joint Workshop 2016 DOI: 10.3217/978-3-85125-528-7-31

Design of an Industrial Robot with Six Degrees of Freedom for Educational Purposes

René Schweidler, Mohamed Aburaia and Corinna Engelhardt-Nowitzki

Department of Advanced Engineering Technologies
University of Applied Sciences Technikum Vienna, Austria
{*rene.schweidler, aburaia, corinna.engelhardt*}@*technikum-wien.at*

Abstract
In state of the art production and assembly lines industrial robots with six axes are widely used to manipulate production goods in all six degrees of freedom in space. Hence, mechatronics and robotics students have to achieve an in-depth comprehension regarding the configuration and adaptation of industrial robots from different manufacturers for applications such as welding, milling, assembling or the handling of components. However, these industrial robots typically cannot be disassembled to explore their internal structure and functionality due to, e.g., warranty reasons. Thus, educational facilities have to use auxiliary means, such as simulation in respective teaching units. To solve that problem, this paper describes the dimensioning and design of an industrial robot with six degrees of freedom for educational purposes, produced by the use of additive manufacturing techniques. Its main strengths are its low costs despite full functionality, its sound maintainability, and the fact that it can be disassembled multiple times by students in the course of, e.g., mechanics, electronics or software development projects. Besides, the proposed educational robot platform has been designed safe-to-use and aesthetically pleasing. Further mechanical structure optimization, the synthesis of the mathematical and kinematic model and control system configuration have to be done in future projects.

1. Introduction

Mechatronics and robotics students have to achieve an in-depth comprehension regarding the configuration and adaptation of industrial robots with six axes to manipulate production goods in all six degrees of freedom in space. Therefore, for educational purposes it is especially important to work with robots that may be disassembled in order to explore their internal structure and functionality. This normally rules out the use of commercial robots beyond manufacturer's designated robot functionalities – usually pure end effector choice, parameter configuration and programming. The use of auxiliary means like 3D-simulation programs is possible, but pedagogically disadvantageous, as the learning experience is impaired by the fictitiousness of virtual robot behavior [Tocháček et al., 2016]. Additionally, educational institutions will typically be subject to strict financial restrictions. Hence, they rely on either loans (i.e., industrial robots that cannot be disassembled) or low-price facilities, eventually self-constructed. Therefore the objective of this paper is to construct a robot platform that suits the aforementioned educational purposes and context requirements.

The technical challenge of this project was to create a robot with full and accessible functionality at a fraction of the costs of a commercial product by using additive manufacturing techniques. Critical attributes to be met in the course of the design process were the educational robot's ability to be disassembled multiple times and to be maintained easily, with as little effort as possible. Besides, the proposed educational robot platform had to be designed safe-to-use and aesthetically pleasing.

Additionally this contribution pays respect to the fact that some authors even state, that the practice of introducing robotics into the academic process is still in an initial development stage (cp. e.g., [Ospennikova et al., 2015]) – at least in specific sectors: the majority of contributions within the current body of literature refers to school education below university level (e.g., [Eguchi, 2010]). Other major developments and respective projects and publications in the field of educational robotics are driven either by major industry players, i.e., robot manufacturers and similar companies (cp. e.g., [Yoo, 2015]) with the disadvantage that disassembly for a deeper understanding is prohibited. Another field of huge activities is the topic of robot competitions (cp. e.g., [Eguchi, 2016]), primarily focusing on robot performance optimization, but rarely on the teaching of advanced robot functional and structural principles at the level of robot engineering master courses within university education.

The remainder of the paper is as follows: section 2 provides a short overview on the field and explains general design principles with regard to the current endeavor. Subsequently sections 3-5 describe design details of the educational robot that has been developed in the course of this project. Finally section 6 draws a brief conclusion with regard to the achieved results and provides an outlook towards future activities.

2. Design principles for educational robotic experiences

The abilities of collegiate robotic and computational thinking and sufficient ways to facilitate the achievement of respective learning objectives within educational programs have been widely discussed in the literature (see e.g., [Miller et al., 2008], [Wing, 2008], [Eguchi, 2010], [Lee et al., 2011] or [Khanlari, 2013]). Although it is not the aim of this paper to provide an exhaustive literature overview, it can be said that the field of juvenile and undergraduate education is well elaborated in particular regarding elementary robot handling, control and programming. However the topic of advanced engineering and mechatronics education has to face further issues. As Alessandri and Paciaroni [Alessandri, 2012] conclude with reference to neuroscience (in particular, cp. [Varela et al., 1995]), an educational robotic experience has to allow for a shift from (more or less passive) observation of a device towards a deep immersion into the system in action. Transferred to the learning target of gaining an in-depth understanding not only from an industrial robots behavior and control, but as well from its functional principles and structures with regard to mechanics, electronics and software development, this leads to the conclusion that advanced robotics and mechatronics students must be provided with the opportunity to construct, simulate, assemble *and* disable a robotic system alternating with physical system-behavior experiments. Thus, before-after explorations could be done, e.g., after having improved mechanical components like a gripper or a joint, after having modified the electronic circuits, after having changed software code or parameters, or even after having totally disassembled and reassembled the whole robot for either maintenance, repair or experimental purposes.

Moreover, this practical education approach supports a further aspect that gains more and more importance in modern engineering disciplines, and especially in the field of mechatronics and robotics: teaching mechanical, electronic and informatics-related skills is a well-known issue. However, the interdisciplinary integration of these (and as needed also further) fields requires greater emphasis, and the same applies for system integration abilities [Gómez et al., 2014]. The educational robot, developed in the course of the current project was also designed for the purpose of strengthening an integrative system engineering approach in theory (robot design and dimensioning) and practical application (robot programming, control and optimization).

Supporting factors to enable robotics learning experiences according to the aforementioned criteria are the ongoing price decline of progressively powerful sensors, motors and micro-controllers together with increasingly widespread additive manufacturing abilities in order to create adequate mechanical parts and actuator components. 3D-printing of synthetic materials has not only become financially affordable. Moreover, meanwhile even basic knowledge of production techniques like e.g., fused deposition modeling (FDM) allows for a rapid design, construction and fabrication of customized robot components with low mass (for further details of filament fabrication refer to e.g., [Allen, 2015]). There is, however, one possible disadvantage to be taken account, when using 3D-printed components: due to expectable inexactness of the printed parts, each robot prototype might have slightly differing attributes. As educational application will scarcely have the need of producing high quantities of identical machines, this can yet be considered as a minor constraint.

Altogether the mentioned developments have enabled the current project. Concretely, a six-axis robot was designed using CAD software that can handle payloads of up to $500g$ mass within a working envelope of $700mm$ in diameter. The belt driven joints were designed to hide all contained drive belts inside the robot in order to ensure safety and to achieve an aesthetically pleasing design. The goals of operator-friendliness and maintainability were obtained by assembling all components in enclosed modular sub-assemblies in order to be able to change each module easily or to adapt just one specific part of the robot. In contrast to commercial industrial robots, there is no need to strictly separate the working range of the robot from human reaching areas by means of a closed assembly cell. Figure 1 illustrates the naming conventions and the structure of the robot.

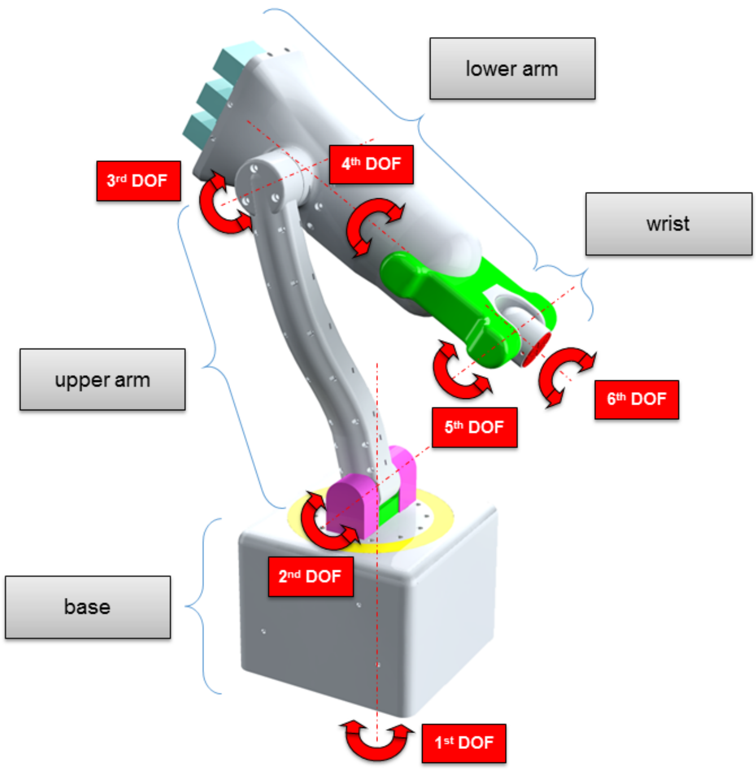

Figure 1. Naming convention and structure of the robot

In this paper the different assemblies are referred to as 'wrist', 'lower arm', 'upper arm'and 'base'. The following metaphor is applied to alleviate the comprehension of the system: The robot can be seen like a human arm. The 'shoulder joint'is mounted to the surface of the table and will be referred to as the 'base'. Next comes the 'upper arm', which connects the 'shoulder'to the 'elbow joint'. In this project the assemblies that are equal to the 'upper arm'and the 'elbow joint'are called 'upper arm'and 'third joint'. Finally, the 'lower arm assembly'is connected between the 'elbow joint'and the 'wrist'.

According to this rough concept, a six-axis robot was designed using CAD software that can handle payloads of up to $500g$ mass within a working envelope of $700mm$ in diameter. In order to provide a save to use platform the robot was designed to hide all moving parts such as belts, pulleys and shafts inside the robot. This at the same time allows for an likable design. In contrast to commercial industrial robots, there is no need to strictly separate the working range of the robot from human reaching areas by means of a closed assembly cell. The goals of operator-friendliness and maintainability were obtained by assembling all components in enclosed, modular assemblies in order to be able to change each module easily or to adapt just one specific part of the robot. A further important design requirement was to provide a platform that is decomposable multiple times without relevant part defects as a consequence of the dis- and re-assembly process. Even after multiple assembly loops, the robot must ensure a sufficient level of precision. This was achieved by introducing index pins in order to prevent from inaccurate re-assembly. Comparably, centering pins are used in order to be able to re-establish the exact coaxial position of every joint after reassembly. All parts were designed and optimized for the use of additive manufacturing techniques in order to enable the re-manufacturing of any part quickly, easily and cost-efficient. A further major design objective was to preferably use standard parts instead of manufacturing customized items. This helps to decrease manufacturing-time and -effort and at the same time makes use of the granted precision provided by supplier-dependent tolerances. In order to cut the maintenance effort to a minimum, only encapsulated bearings were used (no greasing or cleaning).

3. Design of the Base

Due to limitations regarding the maximum size of the 3D-manufactured objects, the base was split into two parts which were screwed together to provide a single solid base. Educational institutions that have access to more advanced equipment or are willing to deviate from the pure 3D-printing approach, could easily design their own robot concepts by means of using a one-piece manufactured base as an alternative. The base has two hollow chambers in order to hold all electronic components and the controller boards shielded and space-saving. As these openings contain all electronic and controller components, the robot can be used in stand alone mode as well as connected to a computer. A further compartment on the bottom of the base hides the drive belt of the first axis and its motor. This additional opening could as well be used to append extra weight (e.g., heavy steel plates) to prevent the base from moving while the robot is used in a stand-alone mode. Another possible use of the bottom compartment is to hold batteries, in case the robot shall be used in locations without electrical power supply, e.g., on fairs or exhibitions. Besides, the batteries take effect as additional weight. As shown in figure 2, the base consists of a cylindrical tube, also containing the motor-holder for the motors of the second and third axis. The first axis is moved by simply shifting the whole cylindrical tube together with the rest of the robot. The motors for the second and third axis are connected to the fork by means of two timing belts. The fork consists of a hollow shaft which is directly powered by the timing belt assigned to the motor of the second axis. The timing belt on the other side of the hollow shaft drives a second pulley inside the shaft.

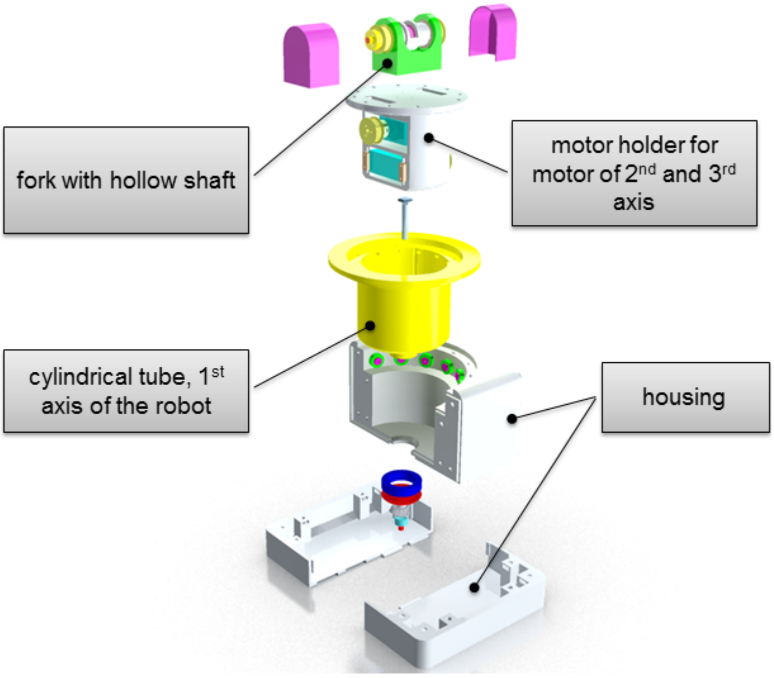

Figure 2. Exploded view of the base

4. Design of the Upper Arm

To reduce the weight of the arm and to maximize the manipulable payload, the motor of the third axis was relocated from the elbow joint into the base. To be able to transmit the torque of the third axis from the base to the elbow joint an arrangement of rods and cardan joints was used inside the upper arm assembly. The upper arm assembly is composed of two main housing parts. It consists of a timing wheel inside the upper arm assembly, which in turn is connected to the timing wheel inside the hollow fork shaft. Finally the torque is transmitted by a bevel gear to the rod assembly and further to the lower arm assembly.

5. Design of the Lower Arm

Another huge challenge was the design of the lower arm and the TCP-gearhead due to heavy restrictions regarding size and weight. Every additional gram that the robot weights implies one gram less that can be manipulated by the later robot. Therefore the construction maxim was to use as few components as possible and within as small space as possible. To provide a counterweight to the handled payload and to alleviate the drive train design, the motors for the fourth, fifth and sixth axis were located at the third joint. The challenge was to place three motors next to each other, but still have their drive shafts positioned coaxial since a parallel position of two or more axes would lock at least one of the three axes. This problem was solved by using a spur gear drive with a various amount of gears combined with a hollow shaft which holds another shaft inside. The spur gears bridge the two dimensional displacement of the motor shafts from the coaxial position. Each of the two coincide shafts inside the upper arm assembly drives a bevel gear drive inside the lower arm which subsequently drives the fifth and sixth axis of the robot using a timing belt connection and another bevel gear box inside the TCP head. The assembly can be seen in figure 3. For the purpose of adjusting the belt tension of the fifth and sixth axis it was necessary to split the lower arm into two pieces, as to adjust the belt tension by a longitudinal displacement between lower arm and wrist assembly. The wrist is accordingly hold in the position by the cover that encloses the lower arm assembly, together with the exposed belt drives.

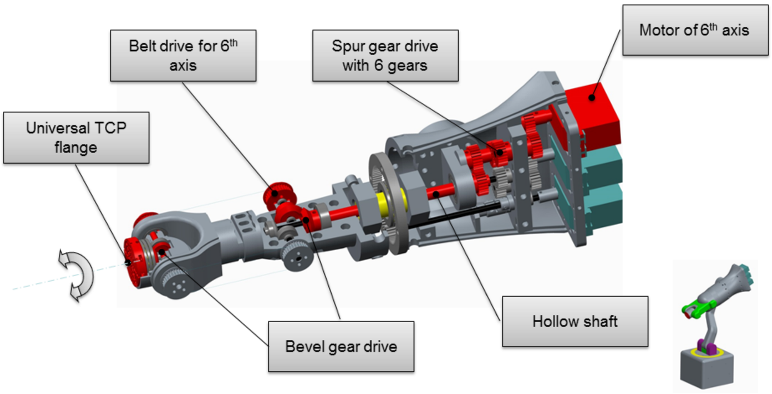

Figure 3. Lower arm assembly with visible torque path of 6^{th} axis

6. Conclusion and Outlook

Concluding, the robot was designed and can be used within future projects. The platform was split into several enclosed, modular sub-assemblies to be able to adapt or change only parts of the robot and to alleviate the final assembly of the robot. Furthermore the robot was designed in the most cost efficient way that was possible with the given resources. Future projects will have to further improve the electronics, the control system and the software to be able to further program the robot. Another possible future project could implement am additional force feedback system by measuring and controlling the current that flows to the motors. This would enable the user to teach the robot by dragging the manipulator in the desired pose and teaching its joint positions. Another big advantage of measuring and controlling the motor currents would be the ability of preventing damage to the mechanical structure or the motors itself by mechanical overload of each joints. Besides this technical improvements, practical evidence within educational context will show the practicability and usefulness of the learning experiences, the robot is able to offer.

References

[Alessandri, 2012] Giuseppe, Alessandri; Martina, Paciaroni (2012): Educational Robotics Between Narration and Simulation. In The World Conference on Design, Arts and Education (DAE-2012), May 1-3 2012, Antalya, Turkey 51, pp. 104-109.

[Allen, 2015] Allen, Robert J.A.; Trask, Richard S. (2015): An experimental demonstration of effective Curved Layer Fused Filament Fabrication utilising a parallel deposition robot. In Additive Manufacturing 8, pp. 78?87.

[Eguchi, 2010] Amy Eguchi (2010): What is Educational Robotics? Theories behind it and practical implementation. In David Gibson, Bernie Dodge (Eds.): Proceedings of Society for Information Technology & Teacher Education International Conference 2010. San Diego, CA, USA: Association for the Advancement of Computing in Education (AACE), pp. 4006-4014.

[Eguchi, 2016] Eguchi, Amy (2016): RoboCupJunior for promoting STEM education, 21st century skills, and technological advancement through robotics competition. In Robotics and Autonomous Systems 75, Part B, pp. 692-699.

[Gómez et al., 2014] Gómez-Espinosa, A.; Lafuente-Ramón, P. D.; Rebollar-Huerta, C.; Hernández-Maldonado, M. A.; Olguín-Callejas, E. H.; Jiménez-Hernández, H. et al. (2014): Design and Construction of a Didactic 3-DOF Parallel Links Robot Station with a 1-DOF Gripper. In Journal of Applied Research and Technology 12 (3), pp. 435-443.

[Khanlari, 2013] Ahmad Khanlari (2013): Effects of Robotics on 21st Century Skills. In European Scientific Journal 9 (27), pp. 26-36.

[Lee et al., 2011] Lee, Irene; Martin, Fred; Denner, Jill; Coulter, Bob; Allan, Walter; Erickson, Jeri et al. (2011): Computational Thinking for Youth in Practice. In ACM Inroads 2 (1), pp. 32-37.

[Miller et al., 2008] Miller, David P.; Nourbakhsh, Illah R.; Siegwart, Roland (2008): Robots for Education. In Bruno Siciliano, Oussama Khatib (Eds.): Springer Handbook of Robotics. Springer Berlin Heidelberg, pp. 1283-1301.

[Ospennikova et al., 2015] Elena Ospennikova; Michael Ershov; Ivan Iljin (2015): Educational Robotics as an Inovative Educational Technology. In Procedia - Social and Behavioral Sciences 214, pp. 18-26.

[Tocháček et al., 2016] Tocháček, Daniel; Lapeš , Jakub; Fuglík, Viktor (2016): Developing Technological Knowledge and Programming Skills of Secondary Schools Students through the Educational Robotics Projects. In Future Academy Multidisciplinary Conference "ICEEPSY & CPSYC & icPSIRS & BE-ci"13-17 October 2015 Istanbul 217, pp. 377-381.

[Varela et al., 1995] Varela, Francisco J.; Thompson, Evan; Rosch, Eleanor (1995): Embodied mind. Cognitive science and human experience. 4. print. Cambridge, Mass.: MIT Press.

[Wing, 2008] Wing, Jeannette M. (2008): Computational thinking and thinking about computing. In Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 366 (1881), pp. 3717-3725.

[Yoo, 2015] Yoo, Juyoung (2015): Results and Outlooks of Robot Education in Republic of Korea. In International Educational Technology Conference, IETC 2014, 3-5 September 2014, Chicago, IL, USA 176, pp. 251-254.