MCI: FPGA-BASED CONTROL OF THE TELEROBOTIC SURGICAL SYSTEM "DA VINCI RESEARCH KIT"

Kohlgrüber S.

Abstract: *The da Vinci Research Kit (dVRK) is an open-source hardware/software platform for researchers based on the da Vinci surgical system. Until now, the torque controller of the dVRK was implemented in analog form, which makes customizations for improved performance difficult. Therefore, the present work aims for the improvement and digital implementation of the low-level control. The use of the internal electronics and encoders enable a model-based controller design which is consequently implemented on the available FPGA. Experiments demonstrate that the new torque controller design yields a performance significantly superior over the originally implemented design. Moreover, the position control allows for high-fidelity trajectory tracking with marginal errors. The comparison between simulation and measurement verifies the validity of the model based on the addressed system identifications, enabling utilization for future adaptations. The improved low-level control allows for more accurate operation, facilitating autonomous surgery and haptic feedback. Moreover, the achieved digital implementation enables users to adapt the low-level control easily in future versions of the dVRK.*
Key words: *Robotic surgery, FPGA-based control, dVRK.*

1. INTRODUCTION

Robotic-assisted surgery offers the possibility of minimally invasive methods for multiple types of surgeries, leading to shorter hospitalizations and hence reducing the burden of health care institutions with limited capacity (Moustris et al. 2011). Representing only one of many advantages, this explains the demand for even faster evolution in this field. One of the most popular robotic surgery systems is the da Vinci surgical system by Intuitive Surgical. However, since it is a proprietary product, the acquisition costs for research institutions are high. To overcome this hurdle, in 2012, the Johns Hopkins University introduced the da Vinci Research Kit (dVKR) (Kazanzides et al. 2014) based on the mechanical setup of the classical da Vinci. As depicted in Fig. 1, it consists of two master tool manipulators (MTM), two or three 7DoF patient side manipulators (PSM), and an endoscopic camera manipulator (ECM). The MTM senses the movements of the surgeon. Consequently, the PSM performs the surgery at the patient side by mimicking the sensed commands with a predefined downscaling factor. The present work aims to improve the control performance of the dVRK.

2. PROBLEM DEFINITION AND OBJECTIVES

The da Vinci Research Kit is a sophisticated system, aiming for maximal modularity and scalability. Based on the desired trajectory, the mid-level control provides target values using the inverse kinematics of the robot to the individual joint controllers. The latter are implemented in the low-level layer using the electronics shown in Fig. 1. Its control, which is responsible for achieving the required motor currents, was previously performed in the form of an analog loop. However, analog control lacks the flexibility for simple configurations and modifications as compared to the flashing of a Field

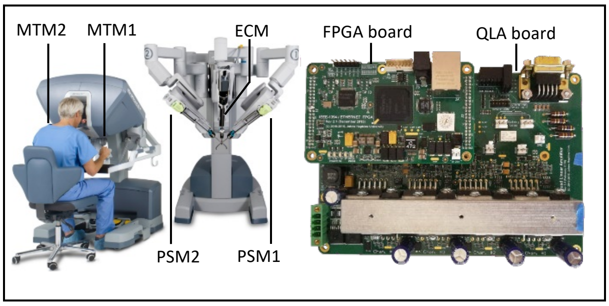

Fig. 1: da Vinci surgical system mechanical setup (Intuitive Surgical 2015) and combined Quad Linear Amplifier (QLA) Board and FPGA board of the dVRK electronics.

Programmable Gate Array (FPGA) or changing the controller coefficients via software. Therefore, the objective of this work is to design and implement the low-level control digitally on an FPGA and to improve its performance compared to the implemented analog motor current/torque control loop. To increase the patient safety, overshoot is to be avoided. Furthermore, position control of the individual axes in joint-space is aimed to be realized in firmware as well. Dedicated emphasis is put on modularity, extensibility, and configurability to facilitate convenient reusability and adaptation to aid utilization for other robotic arms.

3. METHODS

The closed-loop performance of the designed controller is simulated in MATLAB/Simulink upfront before the implementation in Verilog using the Xilinx ISE. The timing of the created controller module is verified in ModelSim using a test bench before the implementation on the FPGA of the real system takes place. For an objective quantitative comparison of performance measures, the central Linux PC is used to control the FPGA registers. The required code is written in C++ using and extending provided libraries. The data recorded using the internal electronics and encoders are automatically stored in log files for further postprocessing in MATLAB.

4. DESIGN

Since the expected variations of moment of inertia and load are very low for the targeted application, the position control is implemented as a cascaded loop using two PID controllers as depicted in Fig. 2. For improved control, the governing parameters are identified using the regression method based on the open-loop system response. This enables to account for influences such as component parasitics, tolerances, or transition resistances. As a consequence, the model is sufficiently accurate to allow its usage for the verification of the torque controller design and tuning of the position controller in simulation within MATLAB Simulink. This enables to obtain higher performance (faster rise times) through the exploitation of nonlinear behaviors, such as control signal saturation, that are difficult to analyze mathematically.

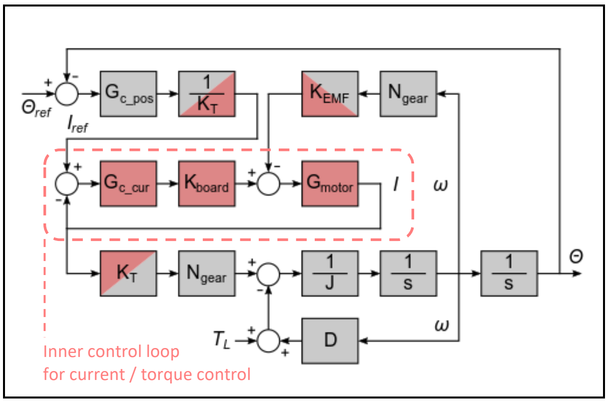

Fig. 2: Block diagram of the cascaded control system for one axis, with inner torque control and outer position control loop. Red and grey denote the electrical and the mechanical parts of the system, respectively.

5. RESULTS

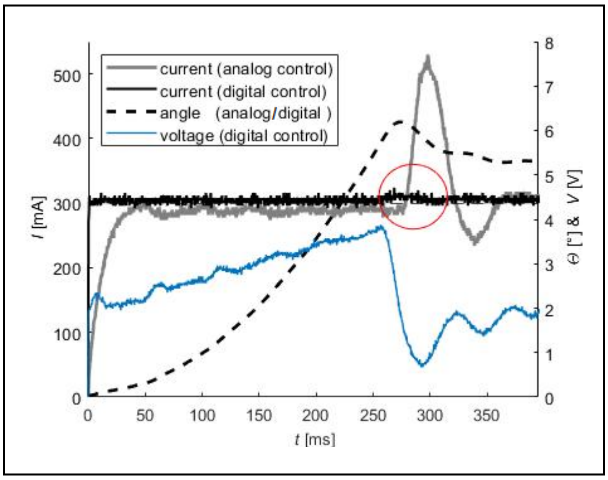

Fig. 3: Step response of old analog and new digital torque controller and their impact on the same load change.

The performance of the new digital controller is superior over the one of the analog controller. Fig. 3 shows the direct comparison of the rise time of 1ms instead of 30ms without any overshoot and the improved reaction to the same sudden load change. While it caused an overshoot of 70% with the old controller, it is nearly completely suppressed with the new digital torque controller (encircled in red). The digital position control on the FPGA enables a high-fidelity trajectory-tracking with errors in the range of fractions of a degree, as exemplarily shown for the first joint leading to Fig. 4. However, the control is implemented and designed for all 7 joints separately which enables an improved response for each individual joint. The chosen register-implementation on the FPGA facilitates further live-customization of the control parameters via SW depending on the applied surgical instrument or desired system response.

AUTHOR

6. CONCLUSION AND OUTLOOK

The present work demonstrates improved control of the dVRK PSM. The digital controller can be implemented on existing dVRK systems by making minor changes to the electronics and will be incorporated in future versions of the open-source electronics design. In addition to the torque controller, a position controller is designed using simulation to cover nonlinear influences such as saturation to obtain high-fidelity tracking performance. Both controllers are implemented on the FPGA. The implemented position and current controllers are currently integrated in the open-source dVRK software stack of the Johns Hopkins University. This allows the improvements to be used by the community consisting of 40 research institutions worldwide. Further, it is expected that the improved control performance will enable other researchers to obtain better experimental results with the dVRK. Given the most recent trend in robotic surgery towards higher degrees of autonomy, the present work has the potential to pave the way for more rapid developments in the field of fully autonomous surgery. A paper summarizing the findings was accepted and presented at the 2021 *IEEE international conference on robotics and automation (ICRA)* (Kohlgrueber et al. 2021).

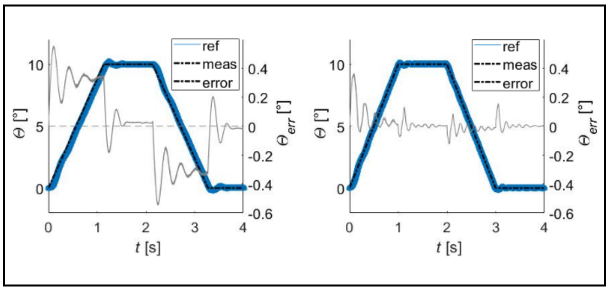

Fig. 4: Comparison of the ramp response with old (left) and new (right) digital position controller implemented on the FPGA.

7. LITERATURE

Intuitive Surgical, 2015. da Vinci robotic system, *Available from:* http://www.intuitivesurgical.com/company/media/images /singlesite.html *Accessed:* 2015-07-13

Kazanzides, P.; Chen, Z.; Deguet, A.; Fischer, G.; Taylor, R. & DiMaio, S., 2014. An open-source research kit for the da vinci surgical system, 2014 *IEEE international conference on robotics and automation*, pp. 6434-6439, 978-1-4799-3685-4, Hong Kong, June 2014.

Kohlgrueber, S.; Kim, Y. & Kazanzides, P., 2021. Model-based Design and Digital Implementation to Improve Control of the da Vinci Research Kit Telerobotic Surgical System, *2021 IEEE international conference on robotics and automation (ICRA),* presented on June 3rd 2021

Moustris, G. P.; Hiridis, S. C.; Deliparaschos, K. M. & Konstantinidis, M., 2011. Evolution of autonomous and semi-autonomous robotic surgical systems*, The international journal of medical robotics and computer assisted surgery, vol. 7, no. 4, pp. 375-392, 21815238*

Ing. Stefan Kohlgrüber, MSc

MCI Innsbruck, Universitätsstraße 15, 6020 Innsbruck, +43 650 444 0845, stefan.kohlgrueber@hotmail.com

Stefan finished the HTL Rankweil in 2011. After 3 years in the field of power electronics with Tridonic, he started his Mechatronic studies at MCI with a semester as an exchange student at Fontys University of Applied Sciences in Eindhoven in 2017 and another semester as visiting research scholar at the Johns Hopkins University (USA) in 2020. He currently holds a position within the Design & Disruptive Technologies team of Leica Geosystems / Hexagon.