Digitus: towards a platform for the characterization of finger biomechanics in fine manipulation

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***Abstract*—This work presents the results of the preliminary experiments performed with DIGITUS, a 2 active and 1 passive Degrees of Freedom (DoFs) fully backdrivable closed kinematics chain planar robot for finger biomechanics investigation. After a brief description of the mechanism and actuation, the paper focuses on the FPGA based control electronics. To test the platform usability two experiments were performed. The first experiment shows the DIGITUS capability to generate force disturbances at the end-effector. The second experiment shows how DIGITUS performs circular trajectories by means of appropriate force-fields at the end-effector.**

I. Introduction

THE characterization of finger biomechanical properties and of the motor control implemented during pinch grasping is a challenging research subject in the fields of neurophysiology, biomedical engineering and gerontechnology. As a matter of fact, understanding the complex neuromuscular interactions involved in finger fine manipulation tasks is a critical issue which has recently been approached from different perspectives. Many studies are devoted to the characterization of finger physical parameters and to understand the control strategies used by the Central Nervous System (CNS) in order to perform different tasks. Zatsiorsky et al. [1] studied the differential effects of gravity and inertia on finger forces during manipulation of hand-held objects. Gao et al. [2] showed the importance of the adaptation of force direction and magnitude for accurate manipulation. Edin et al. [3] discovered that the force distribution among the digits during precision lifting represents a digit-specific lower level neural control establishing a stable grasp.

Moreover, the characterization of finger biomechanics is of interest for both the rehabilitation of stroke survivors, whose manipulation capabilities are in general affected by changes in indices of multi-finger interaction [4], and the biomechanics of aging. As matter of fact, elderly people have significantly reduced force control during pinch tasks, thus reflecting age-related differences in the sharing and coupling of finger forces [5]: aging has a degenerative effect on hand function, including declines in hand and finger strength and ability to control sub maximal pinch force and maintain a steady precision pinch posture, manual speed and hand sensation [6]. What is figured out by the literature is the need for appropriate hardware and software tools for the characterization of finger biomechanics.

DIGITUS is a novel biorobotic platform designed to investigate the finger biomechanics (see Fig. 1). In particular, the DIGITUS platform is mainly ended to the finger pinch task, chosen as reference benchmark for investigating the biomechanics of aging in fine manipulation.

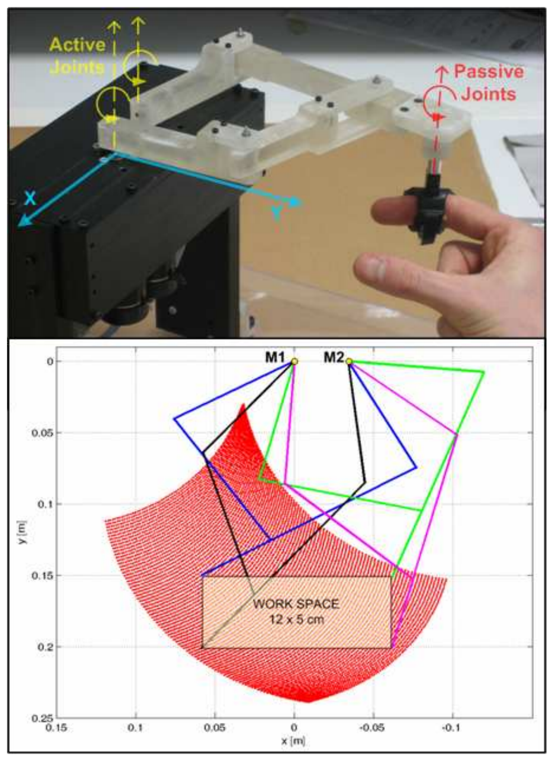

Fig. 1. General view of the DIGITUS preliminary prototype and its workspace.

II. Methods

A. Mechanism and Actuation

DIGITUS is a 2 active and 1 passive DoF fully backdrivable closed kinematic chain planar robot. The active DoFs are actuated by means of two 60 W Maxon RE30 DC motors with graphite brushes, connected to the joint axes by a planetary gear with a reduction ratio of 4.8. The motors are driven by means of two Maxon ADS 50/5 PWM 4 quadrants servoamplifiers. The link lengths were designed to have a rectangular workspace in which

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DIGITUS can generate up to 25 N in each direction. Due to the low reduction ratio and the low link inertias DIGITUS is a fully backdrivable robot, so that it can be both compliant when the finger moves and stiff if, by an appropriate interaction control law, a force field is generated. This behavior is crucial to use DIGITUS as an hardware tool for biomechanics characterization. DIGITUS is equipped with 2 digital 256 counts per turn Maxon MR incremental optical encoders, resulting in 1024 divisions per turn using quadrature multiplication. The mechanical interface between the finger and the platform is modular and easily designed for each specific task.

B. Control electronics

The control system is embedded on the Altera DE2 Board, based on the Cyclone® II Field Programmable Gate Array (FPGA). FPGA technologies allows to integrate an embedded processor Intellectual Property (IP) and an application IP into a System-on-a-Programmable-Chip (SoPC) environment enabling a compact controller design with high performance and low cost [7],[8]. This new electronic family, thanks to its high speed hardwired logic, allows to move part of the burden of servo control loop from a Digital Signal Processor (DSP) to a FPGA [9]. A combination of a DSP and of a FPGA is currently a very popular architecture, where FPGA implements I/O functions according to specific requirements and hardware acceleration for computationally intensive operations. Before the integration of soft-core processors within reconfigurable electronics, embedded control-systems were microcomputer-based, and direct-digital-control (DDC) algorithms implemented in software only. Such solution, in some cases, presents two main problems: the performance is limited by the serial instruction stream and the optimized instruction set is limited by the fabric characteristics of the processor. These limitations may be overcome by using reconfigurable computing systems, which often have impressive performance, as shown by Todman et al. in [10].

Moreover, other advantages of reconfigurable computing include a reduction in size and components count and costs, improved time-to-market, flexibility and upgradeability. These advantages are especially important for embedded applications: as underlined by Giorgi et al. [11], an FPGA-based implementation allows an easy in-field reprogramming of the controller, permitting to perform future upgrading of the control hardware and code “in-situ”, thus not requiring any device disassembly or replacement. Indeed, there is evidence [12],[13],[14] that embedded systems developers show a growing interest in reconfigurable computing systems especially since the introduction of soft-cores which can contain one or more instruction processors. Proprietary instruction processors are now available from FPGA vendors, and often support customization of resources and instructions.

According to Todman et al. [10], custom instructions have two main benefits:

- they reduce the time for instruction fetch and decode, provided that each custom instruction replaces several regular instructions;
- additional resources can be assigned to a custom instruction to improve performance.

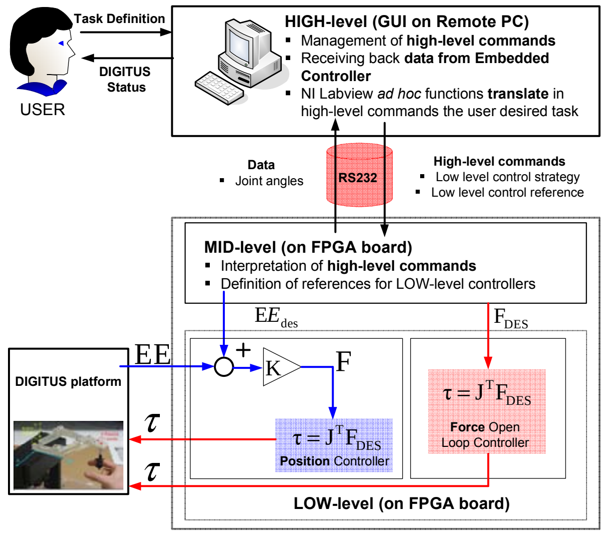

Fig. 2. Block diagram of the DIGITUS hierarchical control structure.

For this reason, in FPGA programming the main issue is hardware-software co-design [15]. This means that the designer has to face the problem of partitioning between software and hardware functions. A mixed hardware-software approach is therefore particularly interesting for control algorithm implementations, which usually require a high computational effort in order to guarantee stability, accuracy and safety of the controlled plant.

C. Hierarchical Control System

By referring to Figure 2 the DIGITUS hierarchical control system is described. Partitioning between hardware based functions and software ones is addressed in this work, moving in hardware the calculation of the trigonometric functions (*sin* and *cos*) required by the direct kinematics and by the Jacobian matrix as a function of the joint angles. The software control-loop runs at 1 kHz on a Nios II/f soft-core processor designed by means of the SOPC builder of the Quartus II environment; data storage is performed by a remote PC which communicates, using the RS232 serial channel, with the digital controller. The PC also produces high-level commands for setting the parameters of the current task. Two strategies have been developed for the DIGITUS low level controller: force control (DIGITUS is compliant) and position control (DIGITUS is stiff). In force control mode DIGITUS generates a target force vector F at the end-effector by regulating the motor torques τ using the geometrical Jacobian $\underline{J}$, such that $\tau = \underline{J}^T F$ [16].

In position control, the force F at the end effector is determined in a closed loop fashion: the error vector between the target and the real end effector positions is converted in a desired force F by a proportional controller: $F = \underline{K}(EE_{DES} - EE)$, where $F = [F_X \quad F_Y]^T$,

$\underline{K} = \begin{bmatrix} K_{XX} & K_{XY} \\ K_{YX} & K_{YY} \end{bmatrix}$ and $EE = [EE_X \; EE_Y]^T$ is the end-effector position vector.

In the experiments performing position control in the following part of this work, the $\underline{K}$ matrix is diagonal ($K_{XY} = K_{YX} = 0$) and $K_{XX} = K_{YY} = 500\,\text{N/m}$.

III. Preliminary experiments

Two preliminary experiments for testing the usability of the platform have been performed. The first was aimed at analyzing the interaction between the human user and the machine, while in the other case the manipulator moves around a circular trajectory without any load being attached to it. According to the first protocol, the human subject simulates a pinch task moving the index finger toward and backward the thumb. While performing this task, the movement is disturbed by step forces applied on the end-effector of the manipulator (force control mode).

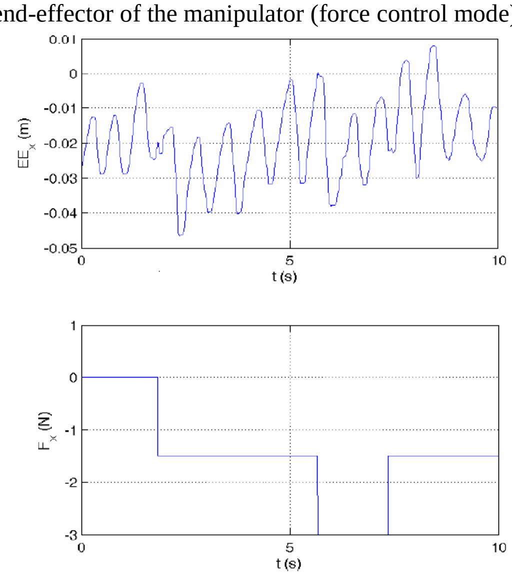

Fig. 3. EE_X vs. time and F_X vs. time for experiment on human machine interaction.

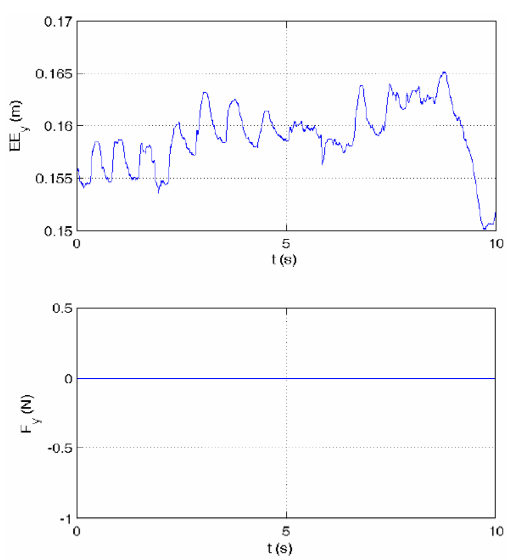

Fig. 4. EE_Y vs. F_Y for the protocol with human machine interaction.

Here follows the protocol for the first preliminary experiment:

1. a null force is applied, so that the user feels the manipulator being free to move around the workspace;
2. a constant force ($F_X = -1.5\,\text{N}$ and $F_Y = 0\,\text{N}$) (baseline) is applied after a certain time (a few seconds) from the beginning of the experiment;
3. the force is increased ($F_X = -3\,\text{N}$ and $F_Y = 0\,\text{N}$) after a certain time and after passing a position threshold;
4. the force is brought back to the baseline level after a certain time;

Figure 3 and Figure 4 report a recording of the proposed protocol. By looking at the recorded end-effector position trajectory it is possible to see the DIGITUS capability to perturbate and track the human index finger trajectory in pinch tasks.

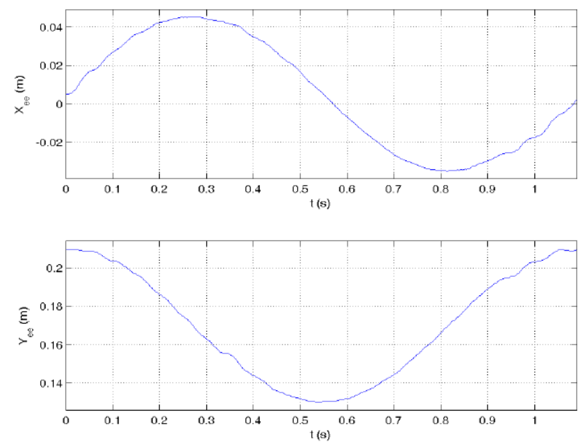

Fig. 5. Plots of EE_X and EE_Y for a circular trajectory with a speed of 0.17 m/s

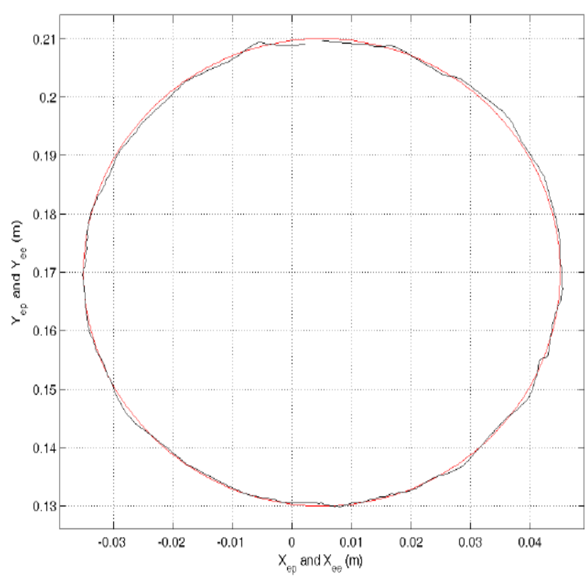

Fig. 6. Scatter plot for a circular trajectory: in red the desired trajectory while in black the performed one.

The second experiment has been performed in order to preliminary evaluate the DIGITUS prototype capability to perform predefined trajectories. In the second experiment the end-effector covers a circular trajectory in position control mode and without DIGITUS-finger interaction. The points of the trajectory are calculated by the high-level controller and sent to the mid-level layer by using the RS232 channel. The high-level controller sends, point-by-point, equilibrium positions which belong to the circumference. Those points are generated by using a custom NI Labview routine running on remote PC.

In Figure 6 the scatter plot for a 8 cm diameter circular trajectory is reported.

From the preliminary results it seems that DIGITUS platform prototype is suitable for finger biomechanics investigation.

IV. Conclusion

The first prototype of the new biorobotic platform DIGITUS for the characterization of finger biomechanics in fine manipulation has been presented in this work. DIGITUS was preliminary tested by means of two experiments: the first – with human machine interaction – showed the suitability of the platform concept for its target applications, while the second – without human machine interaction – demonstrated that the control strategy was appropriate for making the end-effector moving along predefined trajectories.

Once the platform will be definitively completed and tested for guaranteeing its reliability, it will be used with human volunteers in order to investigate neuroscientific models. Furthermore, it will be used to evaluate fine manipulation motor control strategies in elderly people.

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