DEVELOPMENT OF A MODULAR ANTHROPOMORPHIC ROBOT HAND USING SERVOHYDRAULIC ACTUATORS

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Received 31st May 2004

Today's service robotics require humanlike handling systems to interact with our everyday use items. In this paper we introduce the concept of a new modular anthropomorphic robot hand and describe our current work on its realization. Due to its modular architecture of a hand which shall be easily customizable to different applications ranging from handling systems for household helpers to robust finger grippers in factory automation. To drive the fingers, a servohydraulic approach for power transmission is used. Dedicated micro hydraulic cylinders are integrated in the finger segments to actuate the joints. They are driven by a position controlled piston pump. Due to the use of a PTFE enhanced surface coating, slip stick effects and friction are significantly reduced. Our prototype has shown, that the fingers are very robust and even water resistant. The low level control of the robot hand will be done by a reconfigurable system on chip, making future changes of the hardware's functionality possible without changing any printed circuits boards.

Keywords: Hand, servohydraulic, anthropomorphic, service robot

1 Introduction

In today's service robotics the right handling system is vital for the success of the overall system. For scenarios describing the robot as a co-worker or a household assistant, it has to manipulate everyday lives objects in a secure manner to be a serious help for its human antagonist. Most of the tools and objects we are using every day are made for being handled by humans – not by robots. Hence, on the development of an universal gripper system which can handle all of these artifacts, it is obvious to design a technical pendant of the human hand which is with over 20 degrees of freedom the most complex of our outer extremities and probably the most sophisticated in nature. Since the degrees of freedom can be adapted to the application, it seems important to us, that the shape of the robotic hand and its outer dimensions are similar to the human hand. The main reason therefore is on one side, that the ability of handling an object is dependent of the size of the fingers and its geometry. In addition, there is a more psychological one which concerns the acceptance by the end user. Thus, an oversized hand implies high forces and may lead us to avoid interaction with it.

There are two major problems designing a humanlike robot hand: the first one is that biological tissue, in contrast to technical parts, is able to regenerate itself – a fact that is used to compensate abrasion and inner injuries for example caused by overload conditions. The other one is, that we have currently no actuators that have a power density high enough to integrate it into a human sized robot hand achieving a similar grasping force and dynamics at a similar number of degrees of freedom like the natural pendant.

Today, a number of anthropomorphic robot hands are known. Most of them can be categorized according to their actuation principle into three classes:

- remotely actuated hands using Bowden cables (tendon driven)
- integrated electric motors inside the fingers
- fluidic actuated hands.

Remotely actuated hands using Bowden cables are usually driven by electro dynamic motors [1], [2] whose rotary motion is transformed into a linear one using an adequate gear mechanism, like a screw gear or simply a reel where the cable is winded up. Due to the remote actuation, the end effectors can be very compact and lightweight, while the actuators can be mounted for example on the forearm of the robot. Thus it is possible to build human sized anthropomorphic robot hands using this technique. However, Bowden cables have a low stiffness and their flexibility varies with the load, so the end effector cannot be controlled very precisely. Although, the actuation mechanism is complicated since every joint needs two cables which have to be pre-stressed in order to minimize dead times in control. In addition, if a simple reel is used for transmission, there is a constant slip between the reel and the cable which makes additional sensors for the joint angles necessary.

Another approach is to use a fluidic muscle instead of a motor gear combination to drive the Bowden cables [3]. The advantage of this technique is that the pre-stressing of the Bowden cables can be realized easily using a small bias pressure on the actuators and that the grasping forces can be controlled easily by simply limiting the actuator pressure. However, the stiffness of the whole system is further reduced.

An interesting concept underlies the FZK-Hand of the research center of Karlsruhe [4]. This hand is mainly intended for prosthetics and is characterized by its human dimensions and a very lightweight design. The actuation principle is adapted to the Chilean tarantula (Grammostola Spatula) which uses special chambers inside its legs that can be filled with a fluid to actuate the joints. On the back of the skeleton structure of the hand, small pneumatic actors are mounted which directly drive the hand's joints. The main disadvantage of this hand is, besides of the low grasping forces and the very low stiffness, that their joint angles cannot be controlled due to their pneumatic nature.

A significant improvement of the dynamics and the stiffness of the hand is achieved by a direct integration of the actuators into the fingers. There already are a number of robot hands using this approach [5], [6]. Commonly, miniature electro dynamic motors in conjunction with high performance gear stages are used to realize high grasping forces. Directly driven robot hands like the DLR-Hand II and the Gifu-Hand have a human shape but not a human size, which makes them unsuitable for a direct interaction with humans or tools made for them. In addition there is the psychological problem mentioned above when using a bigger sized robot hand in a service robot application since the user might feel threated by the unnatural size and the thereby implied high forces of the hand. However, due to the power density of today's electro dynamic motors, a down scaling of these hands to the size of its human pendant is very difficult and not successfully done until now.

We are currently developing a five fingered human sized and shaped robot hand for both power and fine grasping applications. To customize this hand also to industrial applications, a strong modularity is planned.

Each finger module is designed to have 4 degrees of freedom – three for the flexion and one for the abduction. A tactile sensor matrix [7] build into the finger tips and the palm will be able to detect the contact and force distribution over the grasped object.

The kinematics of the hand should be similar to that of its human pendant so that objects can be handled safely. As we plan to use this hand also in industrial automation, it should be robust enough to withstand the rough industrial environment. Because a robot hand with 20 degrees of freedom is a rather complex system, there is a high demand on the reliability of the single components. To ease service tasks and maintain the operability of the hand, we pay special attention to the modularity and reliability of the components. Figure 1 shows a block diagram of the entire robot hand.

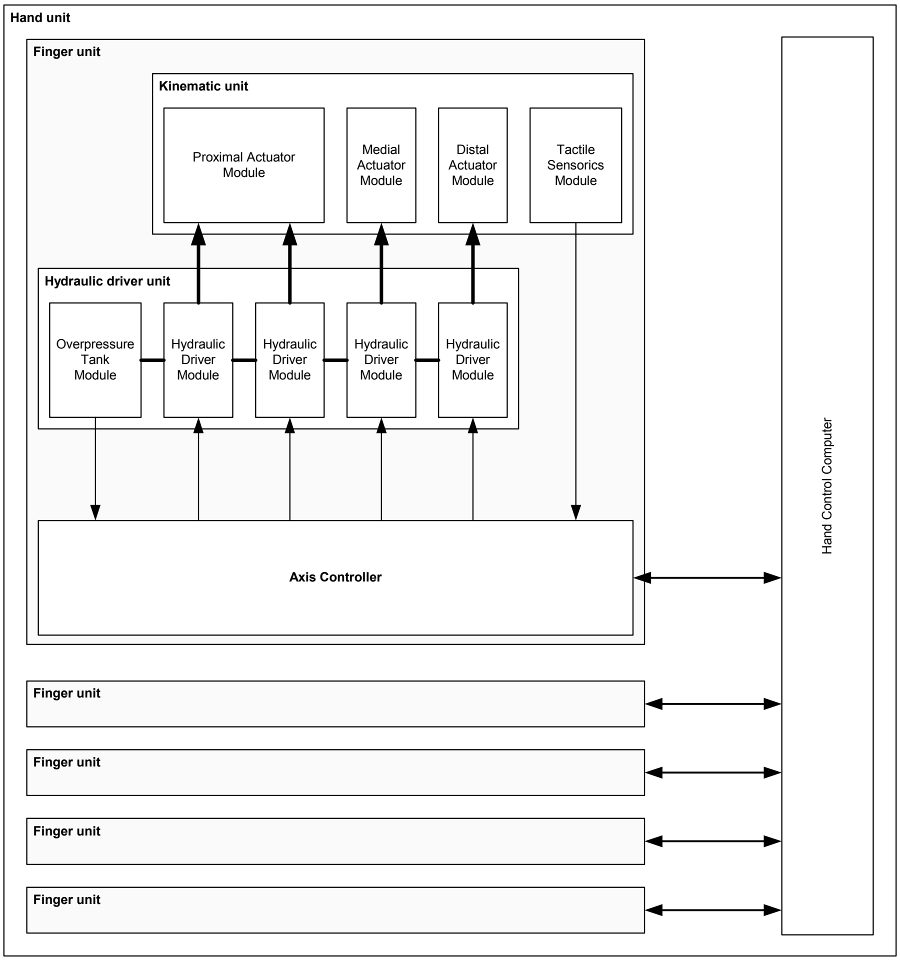

Figure 1: Block diagram of the hand

The outer dimensions of our hand have been approximated to a DIN 33402 95% percentile male human hand. To achieve high grasping forces on a relatively small space, we decided to use a micro servohydraulic actuation principle to drive the hand. As with Bowden cables, the actuators are mounted outside of the hand. But the hydraulic power transmission enables a stiffer actuation path. Besides, the hydraulics allows us to design a robot hand that is very robust and even water resistant, because all components are sealed related to their function. In the following sections the single components are described more detailed.

2 Micro Servohydraulic Actuation Principle

Today's fluidic literature describes plenty possibilities to implement servohydraulic systems for a variety of applications. To determine the most suitable system, we investigated the following three variants for the applicability in our robot hand:

- Actuation by servo valves
- Actuation by micro dose pumps
- Actuation by a regulated piston pump

We have analyzed the complexity of the actuation system, the independency of the single actors, the excellence of the controlled system, dynamics, compactness and the estimated costs.

While the servo valve variant is the standard in common servohydraulic installations, it cannot be scaled down to our needs. Since additional angle sensors are necessary to measure the current joint position, the control of such a system is difficult and the valves needed for an adequate throughput and therefore the demanded dynamics are too big.

With the use of micro dose pumps, the system becomes more compact, but as with the servo valve variant, additional internal sensors inside the joints will be needed to control speed and position. In addition, for a double action control of the end effector cylinder, two pumps are required. Another disadvantage of this pump type is its high sensibility against particles, resulting e.g. from abrasion processes inside the bearings. These particles can lead to device failure.

We decided to use the last variant: the control by a controlled piston pump. The control of speed and position can be done without the need of an angle sensor in the joint.

A block diagram of an actor for a single joint of our hand is shown in Figure 2. It basically consists of two micro hydraulic cylinders (1) (2) which are connected to each other through two flexible pipes (3) filled with a low viscous silicone oil.

While an electro dynamic motor (4) actuates the donor cylinder (1) over a precision ballscrew (5), the end effector cylinder (2) in the finger actuates the joint. If the system accelerates, it is possible that the cylinders aspirate ambient air, which reduces the system's stiffness dramatically and makes it difficult to control the system. To prevent this, the oil circuit is held under a weak overpressure in respect to the ambient. This is done by a pre-stressed tank (6), which is connected to the pipes by two micro ball valves (7) The ball valves ensure that if the pressure in the oil circuit falls below that of the tank, it is refilled. This mechanical mechanism is simple and therefore very robust.

For controlling speed and position of the joint, a high resolution incremental encoder is mounted on the output shaft of the motor, thus it is possible to achieve a very high speed attenuation in the control loop. Of course, a small positioning error has to be accepted at the finger tip due to hysteresis, oil leakage and flexibility effects of the hydraulics.

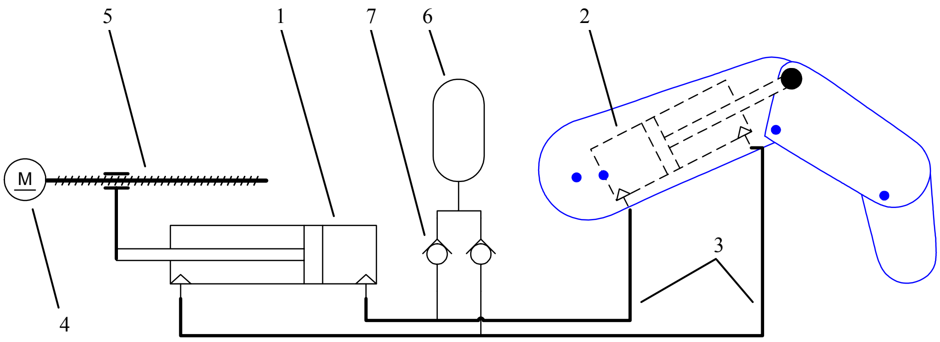

Figure 2: Servohydraulic actuator

To achieve a higher positioning precision, it would be possible to integrate angle sensors inside the joints.

For test purposes, we developed the demonstrator shown in Figure 3. As hydraulic cylinders, we used standard pneumatic cylinders, but filled them with a very low viscose silicon oil in spite of air. In contrast to hydraulic cylinders, their sealings are optimized for low friction on small pressures.

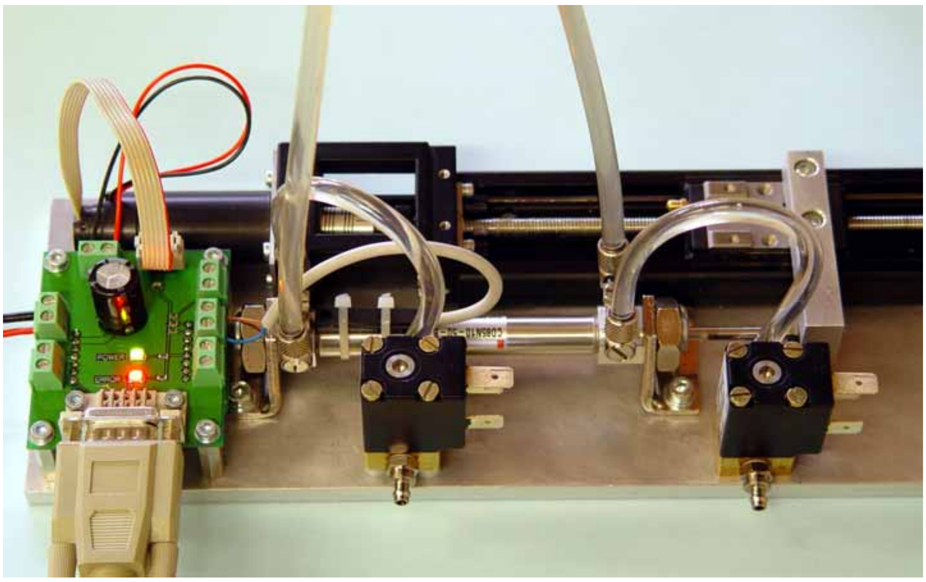

Figure 3: Servohydraulic demonstrator

The cylinders are connected using a transparent polyurethane pipe. The donor cylinder is actuated over a commercially available linear unit driven by a powerful electro motor. Over a motor controller, the piston can be moved with a resolution of approximately 1µm. This corresponds to a angular resolution of the constructed finger joints of 0.006°. Our experiments with this demonstrator have shown, that the actuation by a position controlled piston pump is highly suitable for driving a hydraulic robot hand.

3 Micro Hydraulic Cylinder

The end effector cylinders must be very compact in size in order to be integrated into the finger. For our first prototype we decided to use a piston diameter of 10mm and a stroke of 15mm. Figure 4 shows a cross section of the designed cylinder, which was only intended to demonstrate the working principle. For a real integration into a human sized finger, it is too big.

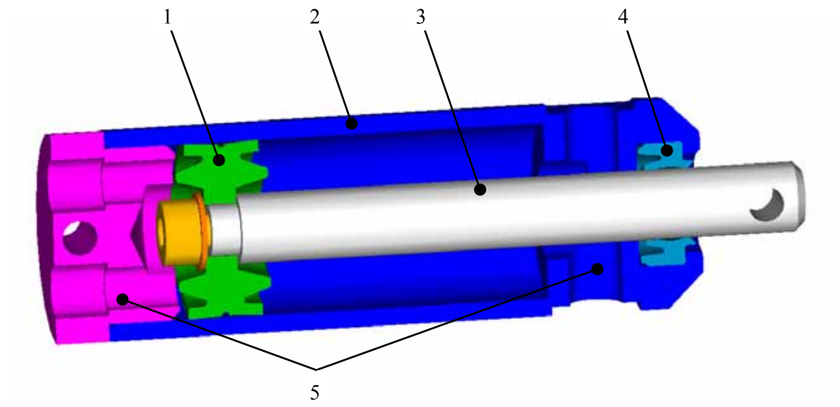

Figure 4: Cross section of the micro hydraulic cylinder

Core of the cylinder is a commercially available compact piston (1) for double acted use. To minimize the friction between the piston and the cylinder tube (2), a special coating technique [8] is used where the surface is anodized and PTFE particles are implanted. In addition, this surface coating, which can be applied to nearly all aluminum and magnesium alloys, reduces the slip stick effect significantly and therefore the position hysteresis. In addition, the surface's hardness is increased to 450 – 480 HV, which makes this coating interesting for surface protection, too. We manufactured the cylinder's inner surface with a roughness of 2µm. After the coating process, a roughness of 5 to 6µm could be measured. This increased roughness is typical for the selected coating process but does not hamper, since the resulting holes in the surface are filled with PTFE. Hence, the performance of the surface-piston-system is better as without the coating, as our experiments can confirm.

The piston rod (3) is made of stainless steel and is mounted on the piston. For sealing the rod, a state of the art rod sealing with integrated wiper ring (4) is used. Due to the excellent gliding characteristics of the coating, the cylinder housing can be directly used as a guiding for the piston rod, thus reducing the number of used components.

The pipes are mounted through two standard M3 fittings (not shown). To make sure that the cylinder can be filled completely with the hydraulic fluid, it contains two more deaeration drills (5) which can be sealed after filling via a plug. Figure 5 shows a photo of the assembled prototype with the mounted fittings. This prototype is tested for friction loss and impermeability at the moment.

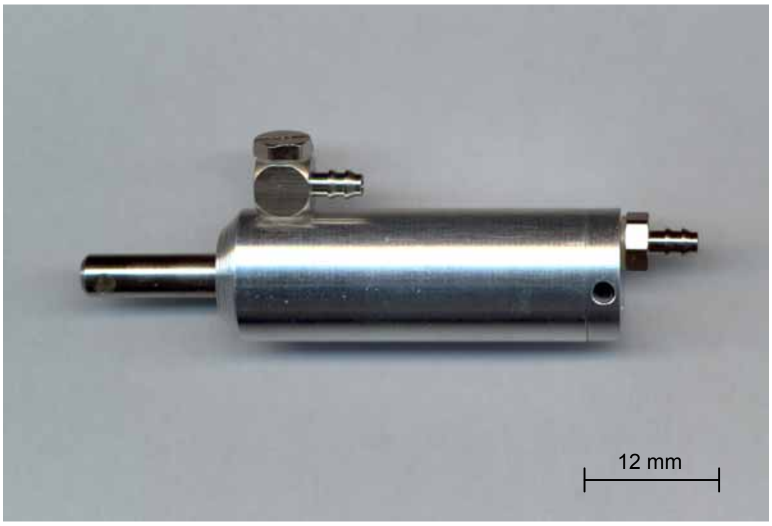

Figure 5: Prototype of the micro hydraulic cylinder (before the coating process)

4 The Finger, An Integrated Design

For an integration into a human sized finger, our first prototype was not suitable, since, on the one hand, it was too big. On the other hand, a lot of components like bolts and bearings would be needed, where every single part can reduce the reliability of the overall system. Thus we decided to integrate the cylinder directly into one finger element in a manner the cylinder tube becomes a part of the segment's housing. Using this approach, we can reduce the number of necessary components to build a very ruggedized finger. Figure 6 shows a 3D model of the medial segment and the distal joint.

The cylinder tube is an integral part of the housing (1) which is closed by the force fitted guide slide bearing (2) of the rod (3) which also holds the rod sealing (4). The rod is mounted with a pin in a guide (5) to generate the rotating motion of the distal segment (6). The pipes are attached by two M3 fittings (7). The cylinder with an inner diameter of 10mm and a stroke of 7mm can withstand an operating pressure of approximately 2 MPa which adds up to a cylinder force of 160N. In terms of figures, this results in a maximum torque of 0.56 Nm.

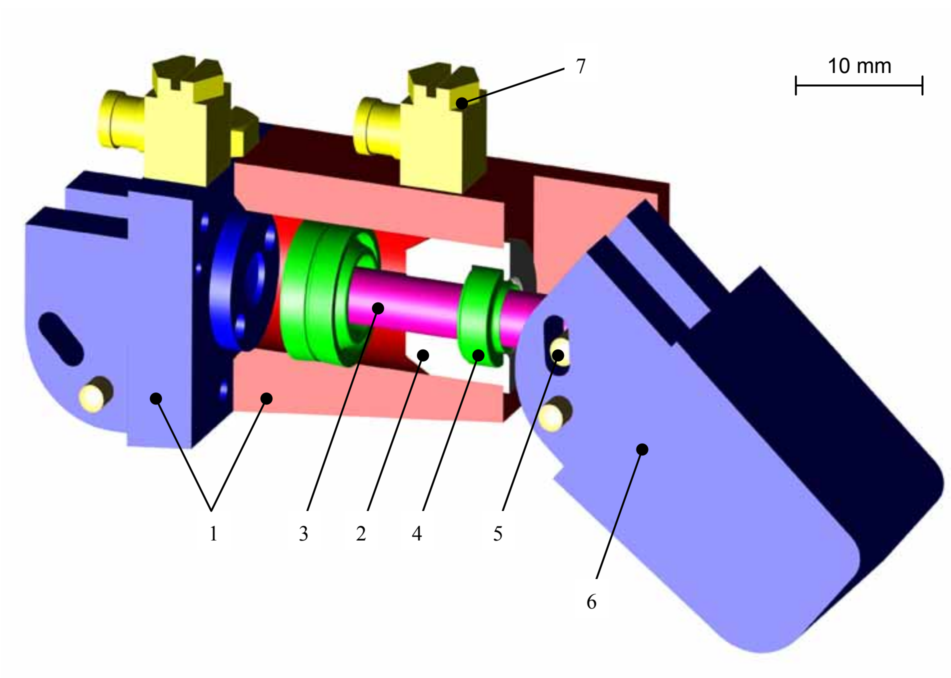

Figure 6: 3D model of the distal joint

The finger prototype itself was manufactured in aluminum and a curable stainless steel, so it is completely water resistant. This first prototype of one finger has two degrees of freedom; one medial and one distal joint. The finger is currently undergoing an endurance test, since we would like to find out, if the precision of the guideway at the force leading-in (5) will be deteriorated when under a permanent load. From this test, we can also devie informations about the endurance and the leakage of the used sealings. This is important to us, if we want to control the finger without any position sensor inside the finger itself, but rather in the hydraulic drive unit, described in chapter 5. Since we are integrating a tactile sensor matrix onto the housing of the finger, we believe, that a high position accuracy is of the finger is not necessary. To grip an object, we rather want to use the pressure profile measured by the tactile sensor as a feedback for controlling the gripping process.

If all the tests will be successful, we plan to expand the finger by a proximal joint additional two degrees of freedom at the end of 2004.

5 Hydraulic Driver Unit

For driving the finger's hydraulic, a modular piston pump system was designed. One of the big advantages of this working principle is, that using the same piston for the pump as for the finger, this pump type is able to directly drive and back drive the finger in a double acting manner. If both lines are hold under a small overpressure relating to the ambient, no air can intrude into the system. The hydraulic driver unit consists of single elements, each of it is driving one finger joint, which can be mounted in-line and connected to the finger using single pipes. Thus, every four pump modules (1) serve one finger. This hydraulic driver unit, which is also shown in Figure 7, is completed with an overpressure tank module (2) holding all pipes at a weak overpressure in respect to the ambient using two miniature non-return ball valves. There is no wiring necessary between the modules since all pipes and seals are integrated. Both modules are very compact in size. The pump module measures 24 x 120 x 60 mm, while the overpressure tank module is only 24 x 100 x 30 mm.

Two pressure sensors are integrated inside each piston pump module to determine the pressure in either fluidic paths to the end effector. These sensors are used to measure the There is also a pressure sensor integrated into the overpressure tank module. Hence the overpressure is realized with a spring, it detects the liquid level inside the tank. Because every hydraulic system has a functionally related small leakage of oil, mainly as a glide film on the rod of the cylinders, there is a small but permanent loss of oil in the system which has to be detected by the control circuit. It must be ensured, that the tank never becomes empty and the overpressure in the system is guaranteed. Otherwise, there is a potential risk of air intrusion which dramatically degrades the mechanical stiffness of the system. gripping force and to limit the system pressure to prevent the pipes from bursting.

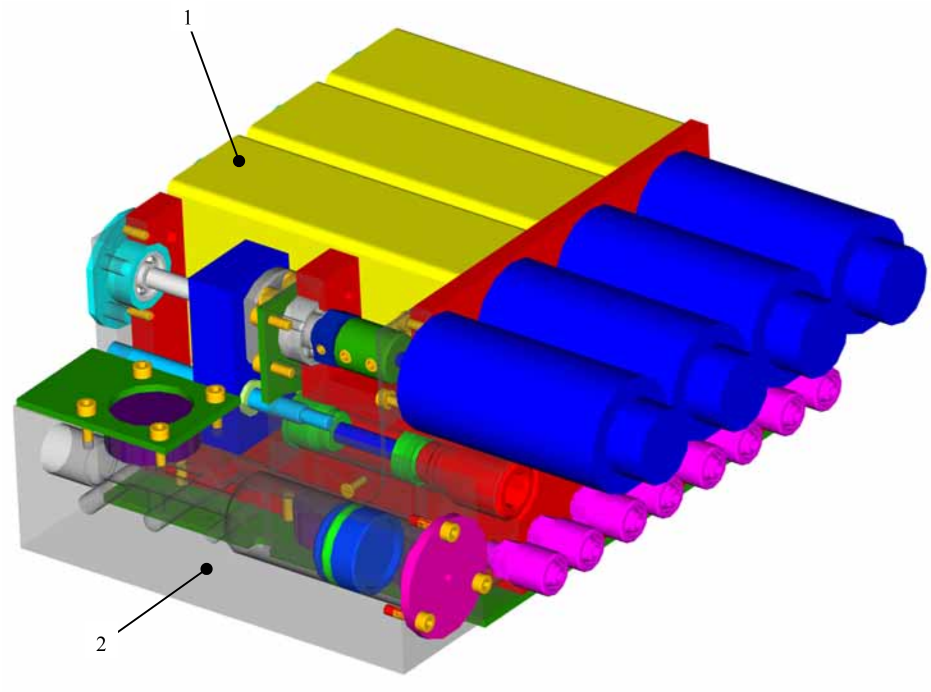

Figure 7: Hydraulic driver unit

6 Finger Axis Controller

The hydraulic drivers are controlled by a finger axis controller we developed especially for controlling many independent axis simultaneously. The controller handles the low level tasks, which means the control of position, speed and system pressure. In addition, the data of the tactile sensors will be interpreted by the axis controller, too. This will allow a closed loop control on tactile information. A block diagram of the hardware is shown in Figure 8. The whole controller is implemented into a single reconfigurable gate array (FPGA). Using a NIOS II soft processor core [9], we achieve a maximum flexibility of our control system. We successfully integrated a hardware-based PI motion controller as a peripheral to the NIOS II, handling the quadrature decoding, the speed measurement, controlling the speed of the motor with a control period of 1ms and outputting the set value as pulse width modulated signal. All parameters can be read and written through a 32-Bit wide interface to the processor's Avalon bus.

The position control loop is currently implemented in software on the NIOS II, thus achieving a high flexibility for our experiments.

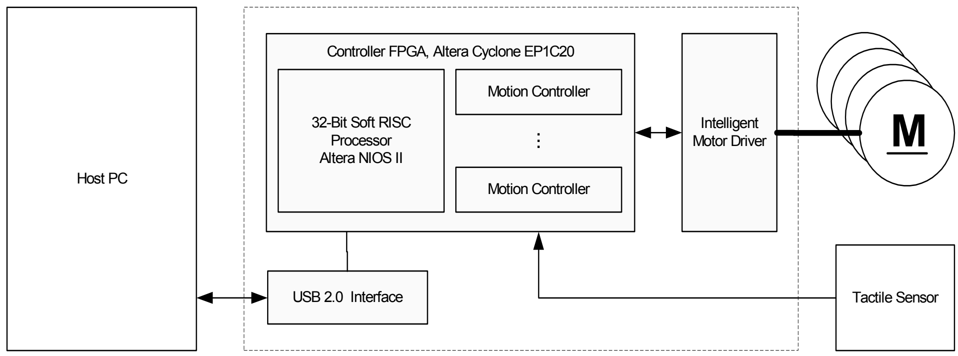

Figure 8: Block diagram of the axis controller

One of the main advantages of this soft processor approach is, that we can simply reconfigure the whole experimental setup without the need to change any electronic circuit boards. Thus, we are able to significantly speed up our tests and even make experiments which were not possible with a hard coded board.

7 Conclusions

In this paper we have described the current development process for an anthropomorphic robot hand using a servo hydraulic actuation principle. We have introduced a modular architecture of a hand which is easily customizable to different applications ranging from industrial handling systems for household helpers to robust finger grippers in factory automation. By building a first demonstrator, we have shown, that the actuation principle using a position controlled piston pump rather then servo valves, is well suited for this kind of application. This approach highly reduces the overall size of the actuation system thus making it possible to integrate it into a human sized robot hand. Losses caused by friction and slip stick effects can be significantly reduced by the use of a surface coating, modifying the tribologic system at the piston sealing. Additionally, we have shown a design of a finger segment where the hydraulic cylinder is an integrated part of the housing, what leads to a significant reduction of components and therewith increasing the robustness and reliability of the fingers. The prototype of this finger is currently undergoing an endurance test for determine its robustness. The introduced finger axis controller consists of a powerful reconfigurable platform, which can be easily adapted to different applications. A soft processor design speeds up the development cycle as well as allows changes in design without redesigning the circuit boards.

Future works include the development of a two DOF proximal joint for the finger as well as the integration of the finger into a hand. Additionally, the control loop between finger movement and the tactile sensor data has to be closed. After integrating the fingers into a hand, we plan to make dedicated test series in realistic grasping scenarios to measure the performance of the actuation system.

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