Spacehand: a multi-fingered robotic hand for space

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ABSTRACT

Despite the technological progress since the first attempts of mankind to explore space, it appears that sending man in space remains challenging. While robotic systems are not yet ready to replace human presence, they provide an excellent support for astronauts during routine maintenance and hazardous tasks. This paper presents the ongoing development of a space qualified multi-fingered robotic hand and highlights the most interesting challenges. The design concept, the mechanical structure, the electronics architecture and the control system are presented throughout this overview paper.

1. INTRODUCTION

There exist a steady desired of mankind to explore the solar system and beyond. While the colonization of distant planets is a distant goal, the scientific community already started exploring very distant bodies and landed on several of them. The risk and complexity associated with the missions require more adaptable tools and among all, flexibility to unknown situations. Up to now human beings are, without a doubt, the most flexible solution but come at a tremendous financial and technical cost, to which the human risk must be added. The development of agile technology for space is a necessary step to diminish the risk and enable a new area of on-orbit servicing, assembly and repair. Robotic technologies that have been successfully applied into the industry in the last 30 years are now mature to move into space and achieve a similar revolution [1]. The DEXHAND and DEXARM [10], [11] project have been done in collaboration with the European Space Agency (ESA) and meant to investigate the potential of hand and arm combination for support of Extra Vehicular Activities (EVA). Similar projects are led by JPL, with the hand of Robonaut [6], or at the University of Laval, with the under-actuated SARAH hand [9]. The final acceptance test of the system demonstrated the high capabilities of a multi-fingered robotic hand for common space tasks. After the completion of the project (cf. Fig. 1), several space agencies have manifested their interest to include the hand in a real mission and only 2 years after the end of the DEXHAND project, the Spacehand project started. It is a mission led by the Defense Advanced Research Projects Agency (DARPA) within which the hand is used as a universal tool among other more specialized ones in multi-year, geosynchronous orbit mission [5]. However, the

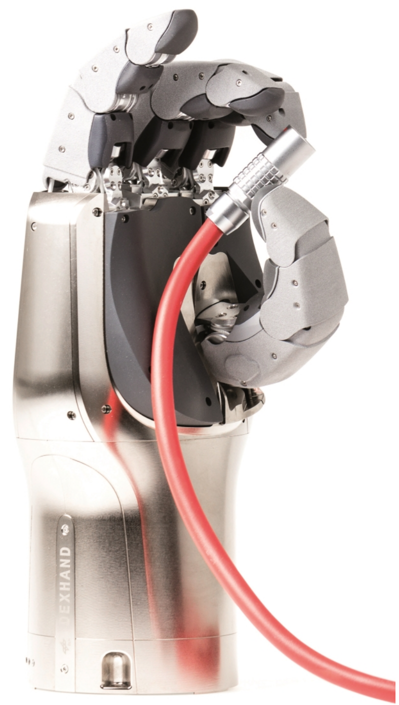

Fig. 1. Photograph of the DEXHAND

DEXHAND development targeted a low earth orbit (LEO) operation environment. Thus, the contribution of this paper is to present the changes that are required to accommodate for the new mission as well as the engineering process that is performed to cross the bridge from the laboratory to space. The work reported is performed in the Institute of Robotics and Mechatronics under internal funding.

The first section presents an overview of the deployment architecture and of the structure of the system. The second section describes the mechanical structure of the hand. It discusses the design changes with respect to the DEXHAND design. The third section focuses on the changes related to the electronics and proposes a shrot discussion of each of the modifications. In section four, an updated analysis of the power distribution as well as the latest thermal results are reported. They show that the thermal simulations offer a sufficient degree of accuracy to predict thermal cases that

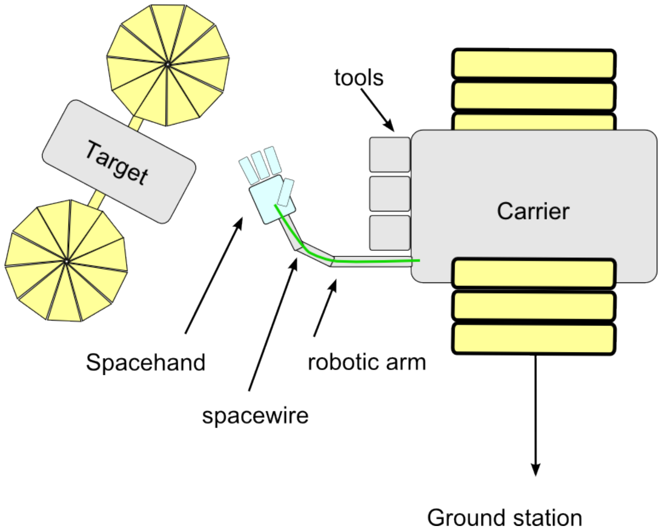

Fig. 2. Overview of the deployment architecture

are difficult to realize in the laboratory. The fifth part gives an overview of the space-related electronic design features and the rational behind many of the difficult design choices.

2. SYSTEM OVERVIEW

The Spacehand is to be used as a multi-purpose backup tool during a GEO mission. Indeed, whereas it is clear that specialized tools are the most appropriate for planned operations, a multi-fingered robotic hand offers an unchallengeable flexibility. Its torque sensing capability makes it particularly appropriate for tasks that require soft interactions, e. g. , the removal of a multi-layered insulation (MLI) cover or the interactions with solar arrays. Together with the long standing history of developments of torque controlled multi-fingered hands [2]–[4], [8] in the institute, the team has a great knowledge database in the design and control of multi-fingered robots and their integration in larger mechatronic systems. The development strongly benefits for the DEXHAND project, a space qualifiable multi-fingered robotic hand, initiated by the ESA in 2011, which provides a solid base for bringing the design into space. The experience gathered during the operation of the DEXHAND is paramount in improving the safety margins of the design. This section presents the design concept and the architecture of the hand.

2.1 Deployment architecture

The Spacehand is a tool to be used in a GEO mission that aims at inspecting and if required, repairing, satellites. Figure 2 depicts the deployment architecture. The hand is mounted on a robotic arm and is using a Spacewire [7] link to communicate. The communication data is packed transmitted to the ground station, with a delay in the order of seconds. The hand is powered by one main supply for operation and a secondary isolated supply for the heating. It has a tool changer socket on the base of the wrist and a small docking mechanism on the side of the wrist used for stowage.

2.2 Hand structure

The Spacehand has four fingers with four degrees of freedom each, with the last two being coupled, resulting in a total of twelve actuated DOFs. Figure 3 and 7 present one DEXHAND finger and the CAD rendering of the Spacehand finger. The joints are actuated by tendons, actuated in turn by motor modules. The software running on a DSP/FPGA implements the communication mechanisms, the impedance control law and several management function.

3. MECHANICAL STRUCTURE

The design is based on modular fingers and motor modules. Using modules allows to produce a large number of identical units and enables the development of unit testing equipment, leveraging the quality control process. The concept keeps the extremities (the fingers) without electronics to improve shielding and robustness. The Spacehand fingers are design to actively produce a fingertip force of 30N with a structural safety factor of 3. The DEXHAND transmission system was using polymer Dyneema tendons that revealed to be extremely durable but present a too high creeping rate for a long term mission. Therefore, a new material was selected for the Spacehand. The following sections are presenting a bottom-up approach of the hand contruction.

3.1 Motor modules and modularity

Electromagnetic actuators have a long standing history of use in space. They offer a wide range of speed and torques, have high power density and benefit from the tremendous research efforts of the automotive and electro industry. The Spacehand motor modules are self contained as depicted in Fig. 4. Allowing, in particular, to develop a dedicated system to record and control the performance of the motor modules before and after they get integrated with the fingers. Once a finger is assembled, it can be tested again, verifying that the sub-assembly was performed properly. Finally, the finished fingers are assembled together. This method ensures that none of the assembly step can occur with out of specification sub-assembly, increasing the quality and reducing the assembly time. The motor unit is based on the Robodrive ILM 25 motor including the gearing of a harmonic drive HFUC 8 with a transmission ratio of 100:1. The whole unit

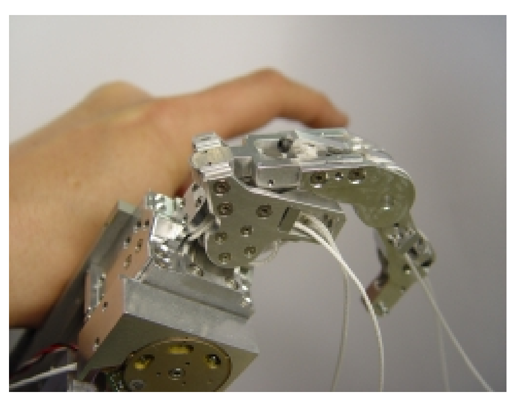

Fig. 3. Finger without housing

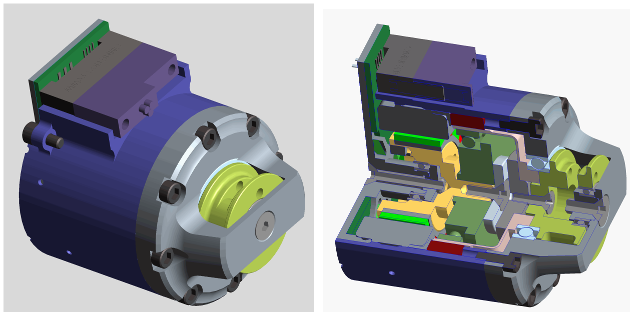

Fig. 4. CAD model of the motor modules

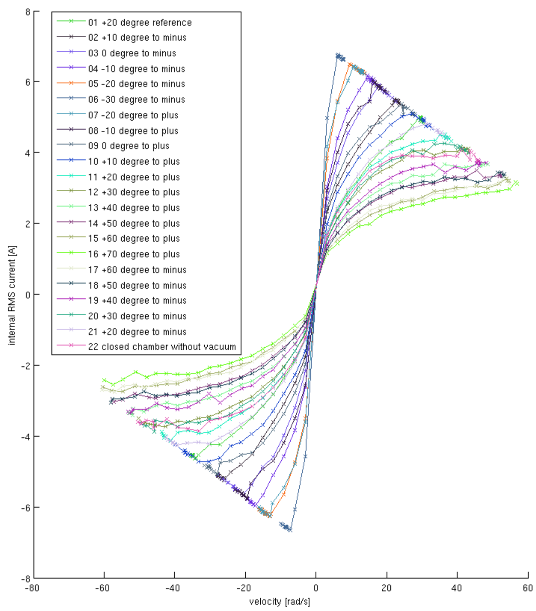

Fig. 5. Friction results for different temperatures and speed under vacuum

fits into a cylinder of 27 mm diameter and a length of 20mm with a weight of 50g. The unit provides a continuous torque of 2.4 Nm with peaks up to 9 Nm which is the maximum peak torque of the gearing. A connection socket is directly available on the motor unit, reducing the assembly time and improving the unit robustness.

An extensive testing of the motor modules has been performed to establish a friction profile according to the temperature. Indeed, a detailed characterization of the lubricant behavior is essential to compute the proper safety margins as well as to detect any possible deviation from the nominal motor module behavior. An example of characterization under vacuum is reported in Fig. 5. The tests have also been repeated after a waiting period of 1 day under vacuum and did not reveal any significant deviation. Future tests will include a variable torque load and a longer waiting period to detect possible cold welding phenomenon.

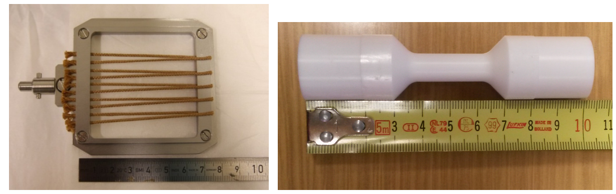

Fig. 6. left: tendon sample before irradiation, right: gliding polymer sample before irradiation

TABLE I
TENDON SAMPLE RESULTS

Condition	Load at rupture [N]	Max. elongation [mm]
Reference	1015	17
Irratiated 693Gy	1000	20
Irratiated 1483Gy	1021	18
UV irradiation	997	31

3.2 Tendon testing

A high performance Zylon fiber, woven by ”Marlow Ropes” has been found to outperform the Dyneema fiber for the application but the data regarding space use of this fiber was insufficient. Therefore, the tendons have been tested extensively. Tests included sun simulation under vacuum, radiation testing with gamma radiation under vacuum, durability test for sliding over different materials and creep test under simulated loading conditions. Simultaneously, the gliding material used for several guiding in the finger base was submitted to the same tests. The ropes have a brown color and a rough surface, c.f. Fig. 6. The results of the tests are summarized in Table I, II. None of the material showed any significant degradation under the expected environmental condition of the mission, thus are used for the Spacehand design.

3.3 Finger structure

The base joint of the finger MP (Metacarpal Proximal) is realized with a Cardanic structure. Two motors are used to drive the base. This configuration advantageously allows to combine the torque of two motors to actuate one DOF of the base joint. The Proximal Inter-Phalangeal joint (PIP) has a fixed coupling with the Distal Inter-Phalangeal joint (DIP) with a ratio of 1 to 1 and is driven by the third motor. Figure 7 shows a CAD model of the finger. From left to right are the MP, PIP and DIP joints. The respective link lengths are 40, 30, and 23 mm. The finger structure is similar to the one used for DEXHAND, however the joints of the Spacehand fingers are using ball bearing instead of gliding joints. It reduces the joint friction and consequently the tendon loads. As a result, the pretension can be reduced and can be maintained with

TABLE II
GLIDING POLYMER SAMPLE RESULTS

Condition	Load at rupture [N]	Max. elongation [mm]
Reference	6108	62
Irratiated 693Gy	6035	34
Irratiated 1483Gy	6106	58

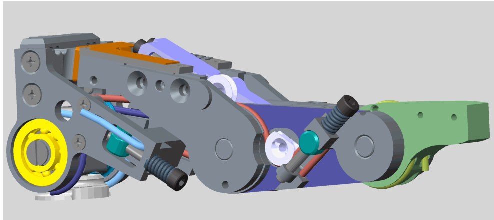

Fig. 7. CAD model of the finger design

small spring placed at the extensors fixture point. The use of ball bearings reduces the allowable maximum load on the joints.

3.4 Finger sensors

Each actuated joint has a reference magnetic sensor at the end of its motion range. It uses a Hall effect sensor placed in the palm structure and a magnet attached to the finger structure. It is worth to note that the reference sensors have been relocated with respect to the DEXHAND design in order to improve the reliability of the referencing procedure. Each of the fingers is equipped with three torque sensors. Two are placed in the base and sense the abduction/adduction torque and flexion/extension torque. The third sensor is placed in the proximal phalanx and senses the PIP/DIP torque through the mean of a lever. Placing the sensor body in the base joint reduces the achievable sensitivity but increases the design robustness. The torque sensors are realized with full strain gauges bridge glued on the structure (cf. Fig. 8).

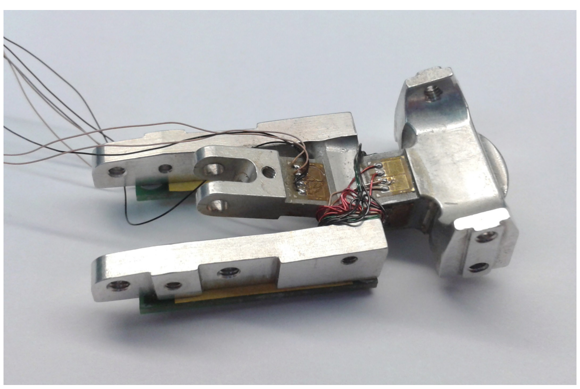

Fig. 8. Strain gauge sensor body placed on the proximal phalanx

Placing all the sensors in the proximal bone simplifies the assembly and the maintenance of the finger. It reduces the bending of the cables to a strict minimum. The current DEXHAND fingers have been used to perform cycle tests on the cable bending and revealed no failures after a very large number of cycles (50000). Vibration tests using several common launchers profiles are planned to verify that the short free section of cable do not enter any undesirable resonance at launch time. Several cable sizes will be tested and the best candidate will be used for the final design. Special care was taken in the design of the sensor body in order to prevent temperature drift, in particular the temperature sensor and

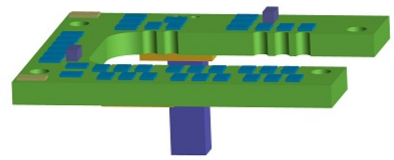

Fig. 9. Finger PCB for strain gauges, heater and temperature sensor (in purple the temperature sensor, oragne heater resistors)

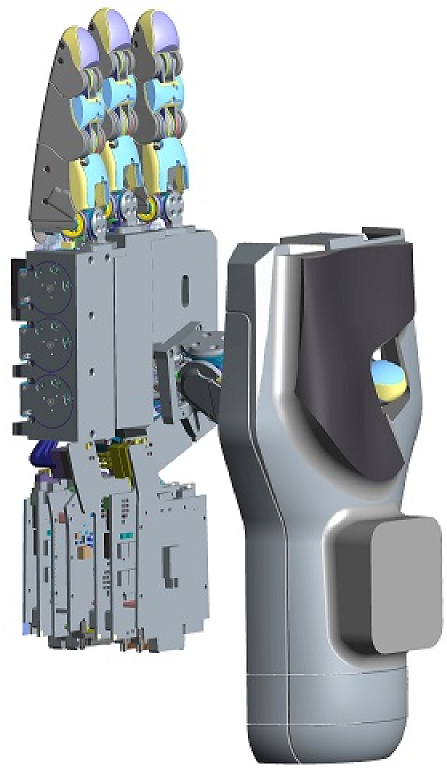

Fig. 10. CAD view of the wrist/palm half shell. The fingers and the PCB stack can be placed in independently

the strain gauge heater are placed directly on the cabling PCB (cf. Fig. 9), reducing the wire count and improving the thermal control.

3.5 Palm and wrist structure

The palm of DEXHAND was constructed in order to minimize the weight of the final structure. During assembly and maintenance, it revealed to be difficult to manipulate and was prone to cable jamming. Therefore, the Spacehand palm builds upon a palmar half cylinder in which all the boards can be placed and the finger modules attached to. The configuration is slightly heavier than the DEXHAND version but allows to insert all cables from the dorsal side (cf. Fig. 10). This approach also improves the thermal conductivity between the electronics and the finger modules. All the finger cables (motors and sensors) are placed on the dorsal side of the palm. Allowing to insert the fingers independently and ensuring a clear fixture of the cables.

3.6 Shielding

The emitted electromagnetic radiations are required to be controlled to avoid possible interactions with the other satellite equipments, in particular communication antennas. In the case of the Spacehand, similar to the DEXHAND, the design allows to create a nearly fully conductive enclosure and thus strongly limit the emission points. The shield corruptions are limited to the tendon insertion points. Conversely, the absorbed radiations can potentially disturb the embedded electronics and create noise on the analog signals. Therefore, the exposed parts of the hand, that is the cabling in the finger bases, are shielded and connected to the structure with a low impedance path.

4. ELECTRONICS

The electronics of the DEXHAND have been designed to be space "qualifiable"', that is most of the concepts and selected component are available in space grade and will function with the same performance level as what has been achieved on the DEXHAND. The experience gathered with the DEXHAND guided a number of wishes for the new electronics. Several unused features are therefore planned for removal and several safety features are added. Finally, the currently envisioned mission itself imposes some design changes, in particular w. r. t. the radiation levels. The hardening of the hand is realized by the combination of three different elements:

- the use of radiation hardened parts.
- housing the whole electronic system in a thick conductive aluminum shell.
- stowing the hand in a protection box, providing an extra shielding thickness and a thermal protection.

However, due to the increased requirements regarding the radiation tolerance, some of the components used for the original DEXHAND desgin must be replaced by larger ones. This led to a new selection of chips and offered new design solutions. The following sections will present and discuss the design choices related to the following features:

- modification of the communication bus, from CAN to Spacewire
- motor controllers for higher radiation levels
- memory layout and memory interface width
- dosimeter

4.1 Spacewire

Spacewire is a widely accepted communication standard developed for Satellite communication system. The use of Spacewire is not a major risk for the project since several of the institute latest robotic platforms, such as the Hand Arm System [8], are also using Spacewire. Several Spacewire cores and LVDS drivers are commercially available for the FPGA and the main technology challenge is the memory connection between the IP core and the existing dual port ram interface. Different LVDS drivers provide a satisfying level of radiation tolerance while satisfying the ECSS standard in terms of speed and electrical characteristics. A breadboard has been manufactured and assemble in order to ensure the proper functionality of the Spacewire core implementation and allow to verify the proper electrical characteristics of the communication lines. The test board is compatible with the existing DEXHAND controller and thus allows an independent development and scheduling path.

4.2 Motor drivers

The major electronic change from DEXHAND to Spacehand is the need for the system to survive several years in GEO. The motor controller used for the DEXHAND design have been tested in house up to 25kRad but this is insufficient for long term GEO operation. The motor controller implemented a six-step commutation with hall sensor feedback (cf. 11, concept A). It provided a gate driving stage, an internal voltage regulation for hall sensors supply and several safety features. In particular, it offered an analog output for current sense and an analog input for a current limit. It allowed to implement a purely analog current limiting circuit, limiting the sum of the motor currents and not the values individually. As a result it was possible to use all the available power for only one motor or share the power equally between the running motors. The power distribution feature is paramount to implement the input power limitation constraints without sacrificing the dynamic performance of the hand.

The replacement design must offer similar or better features in order to offer the same level of performance. The new motor driver solution is based on an integrated motor driver from Texas Instrument. The chip includes internal mosfets, resulting is a small board occupancy, and the required protection circuitry. However, it does not integrate the commutation logic, nor the analog current sensing/limiting features. Therefore, a current sensing circuitry has been added to provide an analog current measurement to be connected to the total current measurement. The current limitation is achieved by masking out the PWM signals directly in the FPGA (cf. 11, concept B). The chip has been tested in house and did not show any performance degradation up to 40kRad (Si), it will be tested for higher radiation doses in the next 2015 campaign.

4.3 Memory

The DEXHAND design was based on a combination of radiation hardened flash memory and terrestrial MRAM coupled to a latch-up detection circuit (cf. Fig. 12, A). The flash memory was used to store the application code and the MRAM to store the application parameters and several long term house keeping values. The usage of the MRAM was limited to a small number of bytes thus taking much space on the board for little functionality. The flash used was 32bits wide and resulted in a complex address translation process for the boot loader code, making the linking and flashing process relatively error prone. Recent studies showed that the reliability of radiation hardened MRAM allows to replace flash memories in many applications. As a result, the Spacehand uses only a single, radiation hardened, two-block MRAM for the application code as well as the system parameters (see Fig. 12). The resulting board size is comparable and offers several advantages: 16bits interface, simplified memory access for firmware upgrade, fully radiation hardened design. The only disadvantage is the potential risk of erasing/modifying the application code in case of software programming error. This risk is mitigated by an address range limitation mechanism enforced by the FPGA, that is, the memory section that contains the application code can only be accessed after a specific unlocking sequence.

4.4 Scientific instruments

The Spacehand aims at demonstrating the usefulness of a multi-fingered robotic hand for space applications. Therefore, a high importance is accorded to the ability to collect scientific data during operation. The system is equipped with a large number of sensors:

- 25 temperatures
- 2 dosimeters
- 5 voltage sensors
- 3 current sensors

and, naturally, the sensors associated with the controller itself:

- 12 motor positions
- 12 motor positions

All the values can be logged at a rate of about 1kHz for several seconds and downloaded later depending on the link availability.

5. POWER DISTRIBUTION AND THERMAL BEHAVIOR

The Spacehand is a highly integrated, high performance robotic system. The compactness of the design results in a high power density and, consequently, requires a precise knowledge of the thermal behavior of the system. Indeed, the fact that thermal exchanges are limited to radiative and conductive phenomenons impacts significantly the design strategies. Most thermal losses that are usually regarded as being insignificant can lead to thermal run-away if the thermal conductivity of the boards to the case is not properly made. Indeed, the thermal resistance between parts can be widely varying if the surface roughtness or the contact pressure is not controlled.

An example of the power distribution in the DEXHAND, board per board, is reported in Fig. 13. Several power mappings have been established according to the operation cases, based on a combination of measurements and simulations. Similar power distribution maps have been estimated for the Spacehand boards and will be verified as soon as the board are produced.

In order to prepare and design a proper thermal control strategy of the Spacehand, efforts have been made to model and verify the DEXHAND power losses and thermal behavior. Figure 14 shows the DEXHAND equipped with the external reference thermal probes (in addition to the 25 temperature sensors in the hand). The thermal model used for the simulation is depicted in Fig. 15. The results of the testing are reported in Table III.

CONCLUSION

This paper presented an overview of the Spacehand project which is a multi-fingered robotic hand developed for GEO operation over several years. The development heavily relies

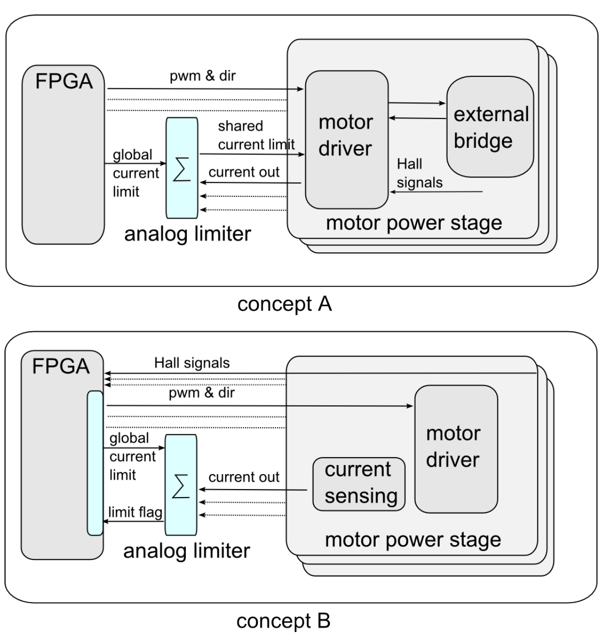

Fig. 11. Board space used by each of the 3 main memory concepts

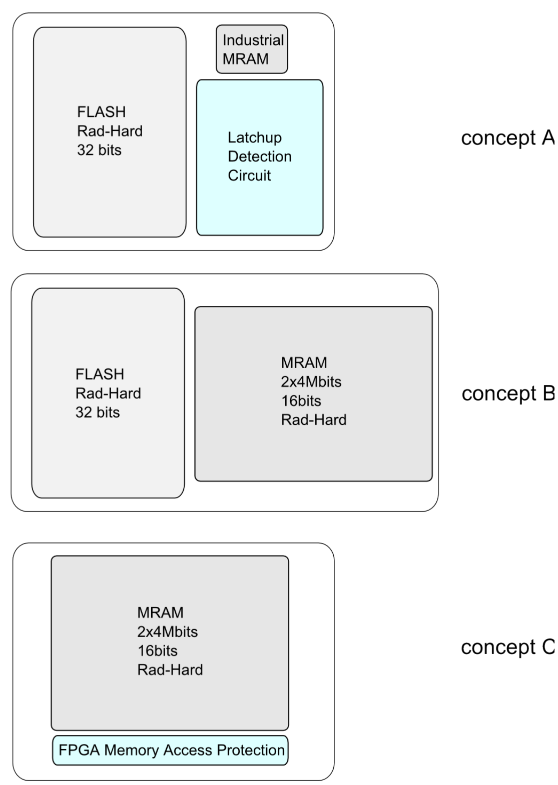

Fig. 12. Several design options for the memories. DEXHAND uses the concept A, for Spacehand, concept C was selected.

TABLE III
THERMAL TESTING RESULTS

Sensor Location	Measured degree Celcius	Simulated degree Celcius	Abs. Difference degree Celcius	Rel. Difference percent
$Analog_1$	$53,43$	$53,61$	$+0,07$	$+0,13$
PI_4	$51,80$	$52,38$	$+0,58$	$+1,12$
PI_3	$51,39$	$52,38$	$+0,99$	$+1,93$
Control	$53,52$	$57,87$	$+4,35$	$+8,13$
PI_2	$50,48$	$51,59$	$+1,11$	$+2,20$
PI_1	$49,97$	$51,60$	$+1,63$	$+3,26$
$Analog_2$	$52,17$	$52,86$	$+0,69$	$+1,32$
Backplane	$54,43$	$55,66$	$+1,23$	$+2,26$
Filter	$54,33$	$56,52$	$+2,19$	$+4,03$

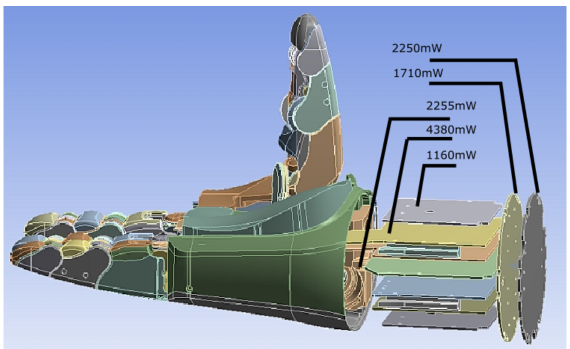

Fig. 13. Power distribution in the DEXHAND depending for the "idle" operation case

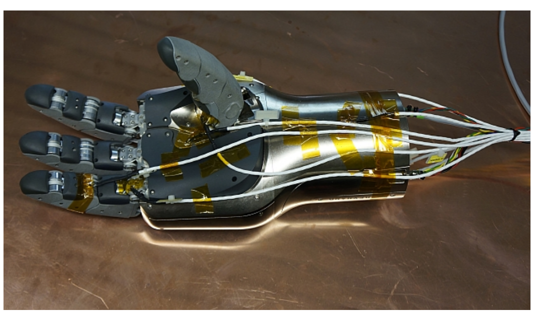

Fig. 14. Hand equipped with the measurement probes

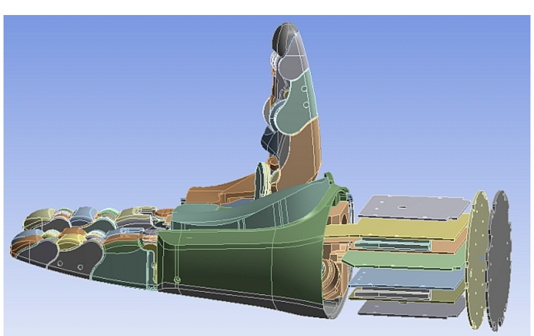

Fig. 15. Thermal model

upon the previous DEXHAND design and on the experience of DLR-RM in multi-fingered robot hands.

It is noteworthy to remark that the thermal behavior is primarily dictated by the digital electronics since that are permanently running. The thermal losses in the power chain are larger but can easily be mitigated by slowing down the operation if required.

A major change with respect to the DEXHAND concept is the change of radiation load and type due to the orbit and mission duration. It resulted in a change of design for the power inverter parts, based on Texas Instrument integrated motor driver. The current system is designed for a total dose of about 50kRad, which should provide a safe operation during of 5 years in GEO.

Unsurprinsingly, the tendons are the most critical elements of the drive system and, consequently, have been tested extensively. Zylon, a new tendon material was selected because the previous material was inappropriate for long term operation. A change of technology for the joints and a redesign of the tendon fixtures also increased the safety margin with respect to the tendon durability.

The internal computing resources, combining the floating computation speed of a DSP and the low-level parallelism of a FPGA allow the hand to achieve a real-time 1kHz joint impedance control and provide advanced analysis and upgrade functionality. The Spacehand communicates at a speed of 2Mbit/s over a spacewire LVDS connection as needed for the mission but its design should accommodate higher communication speeds.

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