Design and Development of a Dexterous Master Glove for Nuclear Waste Telemanipulation

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Abstract: The rise of the nuclear industry in middle of the last century required the development of remotely controlled robotic solutions. Researches on radioactivity and its applications were initially performed in gloveboxes and hot cells with which operators can efficiently and safely access dangerous materials at distance using telemanipulators. Owing to the relatively limited variety of the objects used in such environments, and to the fact that they can usually be adapted for remote manipulation, it was possible to efficiently grasp them using purely mechanical or robotic 6 degrees of freedom (DoF) master-slave systems equipped with bi-digital grippers on the slave side and simple handles on the master side. Such solutions, which were perfectly adapted for handling a limited quantity and variety of radioactive material, are however no more sufficient when processing huge quantities of nuclear waste accumulated over time and/or produced at the occasion of dismantling operations occurring decades later at the end of the nuclear power plants lifecycle. The quantity and diversity of nuclear waste require more efficient and versatile systems. To answer this challenge and increase the operators' productivity, we developed a novel dexterous master-slave system composed of a tri-digital master glove and a remotely controlled three fingers dexterous gripper. This paper presents the design and development of this master hand device. We first introduce its design rationale, then we present its electro-mechanical design, with details on the kinematics, actuators, sensors and controller, and finally its integration in a master-slave system which is used to validate its ability to perform dexterous telemanipulation.

1 INTRODUCTION

The rise of the nuclear industry in the middle of the twentieth century required the development of efficient processes allowing to exploit its extraordinary power for both military applications and for the production of electricity. Owing to the health hazard associated with radioactivity, it was not possible to take irradiated materials in hands as in other industries. It was of critical importance to develop technological solutions allowing to remotely grasp and manipulate radioactive objects without exposing operators to danger. The solution found by researchers and engineers was to use gloveboxes and hot cells with which operators can access dangerous materials safely at distance using remote manipulation means, among which telemanipulators are the most advanced and efficient solutions. Thanks to the relatively limited variety of the to-be-grasped objects, it was possible to adapt them for remote manipulation, and 6 DoF master-slave systems equipped with bi-digital grippers on the slave side and simple handles on the master side were sufficient for these pioneering activities. Indeed, various telemanipulators, being either purely mechanical systems of robotic devices, were developed and used in nuclear installations (Köhler, 1981; Vertut, 1984). Such systems, especially those benefiting from computer assisted telemanipulation functions, prove to be very efficient and are still in use today, for example in the recycling plant of La Hague in France (Piolain et al., 2010; Geffard et al., 2012).

Such solutions, which were perfectly adapted for handling a limited quantity and variety of radioactive material, are however no more sufficient when dealing with dismantling operations required decades later at the end of the nuclear power plants lifecycle, or for processing the huge quantity of waste accumulated over the years of exploitation of these installations. The quantity and diversity of nuclear waste materials require more efficient and versatile systems. This was precisely the objective of the

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RoMaNS (i.e. Robotic Manipulation for Nuclear Sort and Segregation) project, financed by the European Horizon 2020 research program, to advance the state of the art in telemanipulation and develop novel solutions to solve the challenging and safety-critical industrial problem of sorting and segregating such irradiated material (ROMANS, 2015) (WNN, 2015) (Marturi, 2016). To better understand the problem, it can be recalled that in the sole UK for example, intermediate level waste amount to about 1.4 million cubic meters, part of this legacy nuclear waste being very old (first nuclear operations date back to the 1940s) and poorly characterized. Indeed, in many older nuclear sites, waste of mixed contamination levels are put together in several thousands of storage containers, some with even unknown contents. It is now time to clean up this waste stock and develop a more sustainable solution to store them. Therefore, it is of primary economic importance to put each waste item in an adequate container. Low level waste in particular must be placed in low-level storage containers, rather than occupying extremely expensive and resource intensive high-level storage containers and facilities. This sorting process requires opening thousands of legacy waste containers, extracting their potentially very various contents (pieces of fuel rod casing, contaminated tools and rubble, irradiated suits, rubber gloves, etc.), and sorting and segregating the most highly contaminated objects. This process can only be performed using remotely controlled robots due to the high radiation levels of some waste material, and state-of-the-art simple 6 DoF teleoperated robots are not a viable solution therefore in the longterm. Indeed, being equipped with simple bi-digital grippers, they are not adapted to grasp all kinds of objects being present in the containers. One of the aim of the ROMANS project, along with mixed autonomy solutions allowing to increase operators' productivity, was to develop more dexterous and versatile telemanipulation means. As will be presented below, both a new three fingers slave hand and a novel tri-digital input device, object of this article, were designed to answer this challenge.

Fortunately, despite there were relatively few advancements in dexterous teleoperation in the nuclear industry in the last decades, huge progress has been obtained in the meantime in dexterous force feedback robotics and VR haptics. The requirement for anthropomorphic devices able to assist humans in force demanding applications (e.g. military, civil security, firemen, and even industry) or to restore lost motor abilities (e.g. rehabilitation, disabled people assistance), as well as the rise of Virtual Reality applications, led to the development of numerous arm and hand orthoses, exoskeletons and master devices (Bogue, 2009) (Foumashi et al., 2011) (Heo et al., 2012) (Gopura et al., 2016) (Perret and Van der Poorten, 2018).

The lessons learnt from these works were taken into account for the development of the tri-digital hand master device presented in this article. Section 2 introduces its specifications, sections 3 and 4 present its design and implementation, and section 5 concludes this paper.

2 SPECIFICATIONS

2.1 Teleoperation Set-up

2.1.1 Controlled Slave Robot

To cope with the aforementioned challenge, a novel reconfigurable and underactuated robotic hand was developed. As shown in Figure 1, this hand is composed of three fingers with similar kinematics. Each finger is composed of two phalanges and has two DoFs in flexion. This mechanism is underactuated, with only one actuator controlling the two flexion DoFs. Coupling rods and springs allow to passively adapt to the grasped objects' geometry as proposed in (Birglen and Gosselin, 2004) and (Birglen et al., 2008). The distal phalanges are covered with a soft polymeric envelope in order to increase grasping robustness when an object is held in hand, and a sharp end is provided in order to allow for precision grasps. An additional abduction-adduction DoF allows jointly reconfiguring the two fingers that appear the closest in Figure 1. In extreme configurations, these fingers point towards each other, or towards the third and fixed finger, with intermediate configurations favouring circular and spherical grasps as shown in Figure 1.

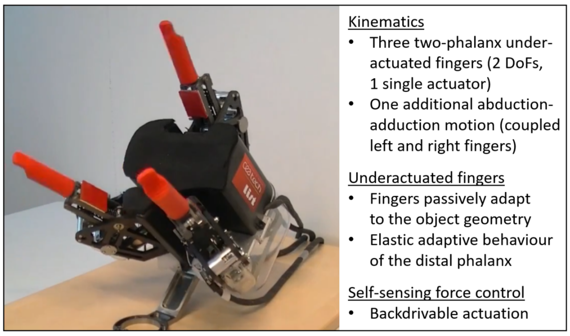

Figure 1: CEA LIST's three fingers slave hand.

Such a three fingers design proves to be sufficient for coarse gripping and manipulating the to-be-sorted objects, yet it remains simple and rugged when compared to five-fingers hands which would be too fragile for such harsh environment. As shown in Figure 2, it can generate power, intermediate and precision grasp patterns (Feix et al., 2009), and it is capable of grasping a large variety of objects similar in size and weight to those encountered in nuclear waste containers. It was mounted on a large capacity slave robot (ABB IRB 2600, see Figure3).

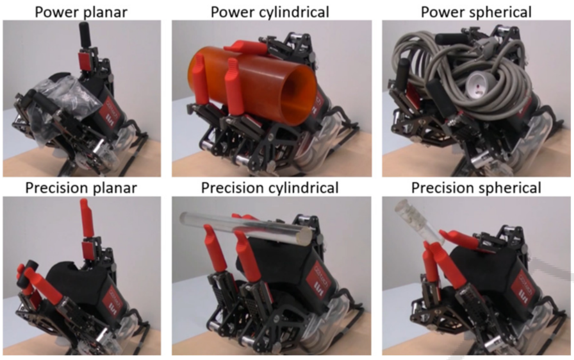

Figure 2: Illustration of the possible grasps of the CEA LIST's three fingers slave hand.

Figure 3: Example set-up on the slave side.

It is worth noting that to efficiently perform dexterous operations, the human being often makes use of both hands. This configuration allows some level of parallelization, and most importantly to concurrently perform complementary operations (e.g. holding a container with one hand and opening the lid with the second hand, opening a container and grasping an object inside it, grasping an object and making an operation on it, etc.). This configuration was used here, with one robot carrying a simple gripper used for rough operations, and the second one equipped with the three fingers gripper allowing to perform dexterous operations.

2.1.2 Master Console

To allow for an intuitive and efficient control of a bi-manual teleoperation set-up like the one presented above, a master console equipped with two input devices is required. A usual 6 DoF master arm (like for example the Virtuose 6D TAO from Haption shown on the left side of the figure below) is sufficient to control the first robot. It is however not the case for the control of the second arm equipped with the three fingers gripper. As shown in Figure 4, a more advanced solution is required, allowing fine control of the dexterous gripper and force feedback on both the palm and fingers. To do so, we developed a novel dexterous hand master whose design drivers are presented below.

Figure 4: Master slave setup equipped with bi-digital and three fingers grippers.

2.2 Design Drivers of the Dexterous Hand Master

The following criteria were considered for the specification of our dexterous hand master:

1/ Dexterous manipulation: in order to control a three fingers slave hand, the most logical solution is to use a tri-digital hand master. A more general study of manual interactions shows that this is also an interesting compromise between manipulation capabilities and complexity (Gonzalez et al., 2014). As illustrated in Figure 5, the percentage of our daily life rendered possible when using three, respectively four or five fingertips (patterns M4, resp. M5 and M6) is between 22.4 and 42.7%, resp. 28.7 and 54.5% and 33.3 and 61.7% depending on the type of activities performed (rough manipulation, fine manipulation or manual exploration of the environment). Using more fingers naturally allows reaching higher scores in theory. However, when considering the use of master input devices to perform such actions, this is not necessarily the case in practice. Indeed, increasing the number of fingers the input device can track and apply force feedback on requires a higher number of DoFs, more links, joints and actuators. This added complexity tends to reduce the range of motion of the fingers, limit the force and stiffness available on each finger, increase friction and inertia, and globally limit the real efficiency. As an example, it appears that the three fingers IHS10 glove (Gosselin, 2012) is more efficient than the four fingers Rutgers Master II (Bouzit et al., 2002) or the five fingers Cybergrasp (Aiple et Schiele, 2013) when taking into account the limitations of the fingers motion, the force capacity and the stiffness along with the number of fingers.

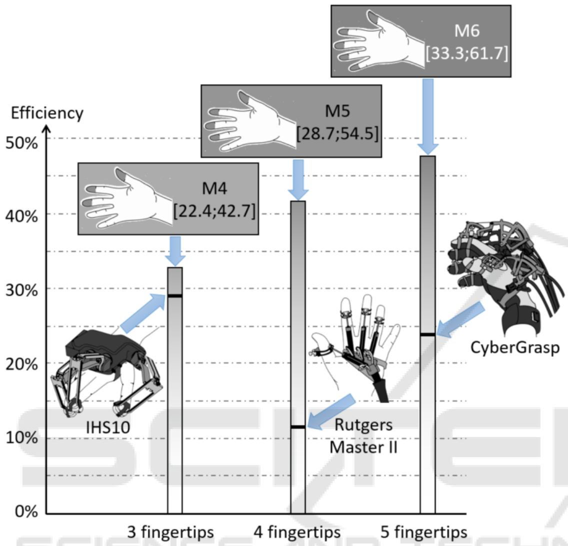

Figure 5: Comparative study of the interaction efficiency of some existing three, four and five fingers input devices (adapted from (Gonzalez et al., 2014)).

As a consequence, we will make use here of a three fingers device. As shown in Figure 4, this device will be mounted at the tip of a Virtuose 6D and attached to the palm, in order to allow for haptic feedback on both the palm and fingertips. This solution has the additional advantage of allowing to compensate the weight of the glove, rendering its use totally transparent for the user who has not to carry its weight on the hand.

2/ Universal fit: as explained in (Gosselin et al., 2020), two types of dexterous interfaces can be found in the literature. Exoskeletons have links and joints similar to the hand, and they are attached to every phalanges on which they can independently apply forces. They allow simulating both precision and power grasps, at the price however of hard mechanical constraints as their joints have to be roughly aligned with the fingers' ones. Hence, they must be tuned to each user, which is not convenient for a universal device that can be used by different operators. On the contrary, fingertip interfaces are fixed only on the palm and distal phalanges, and their geometry is less restricted, making them easily usable by different users. Their design is also much simpler. These advantages led us to focus on fingertip devices. To allow for natural interactions with the palm and fingers, links and joints have to be positioned and dimensioned so that the robot does not limit the fingers' movements.

3/ High transparency and force feedback quality: haptic interfaces should be transparent in free space, i.e. display a mechanical impedance that is sufficiently low for the user to forget their presence. They should also be able to provide high impedances to simulate realistic contacts with stiff surfaces. This contradiction usually leads to a compromise between a high transparency in free space (i.e. low friction and inertia) and realistic force feedback in contact (i.e. high forces and stiffness). Here, we will exploit the fact that the slave hand has only one actuator per finger to control it with a glove having also only one actuator per finger, allowing to greatly simplify the design and favour a high transparency.

3 ELECTRO-MECHANICAL DESIGN

3.1 Overview of the System

The tri-digital master glove is illustrated on Figure 6. It is composed of a base plate fixed on the palm and 3 robots attached to the distal phalanx of the thumb, index and middle finger, allowing to track and apply forces on these fingers.

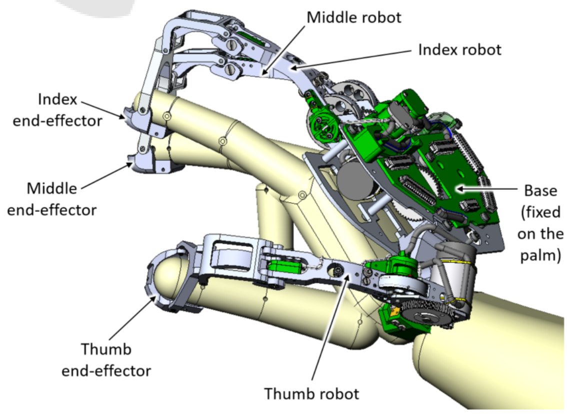

Figure 6: Overview of the tri-digital master glove.

This design was inspired by the dexterous interface with hybrid haptic feedback for Virtual

Reality applications presented in (Gosselin et al., 2020). It was adapted to our requirements (3 fingers with one DoF force feedback each) and improved (novel sensors and simplified end-effectors).

The base is dimensioned so that the index and middle robots' and fingers' abduction-adduction axes are as close as possible (they are theoretically aligned for an adult man corresponding to the 50th percentile of the population).

As shown on Figure 7, each robot is composed of 6 links (7 for the thumb, owing the requirement to make thumb opposition), allowing to move the fingers freely in their entire workspace. Joint sensors are integrated in the abduction-adduction, proximal flexion and intermediate flexion axes, as well as on the tilt axis of the thumb, allowing to compute the end-effectors' positions in space. Each robot is provided with a single actuation unit enabling torque feedback on the proximal flexion axis, hence force feedback at the fingertips roughly normal to the finger pulp. These actuators are equipped with high resolution incremental encoders, ensuring high quality position control.

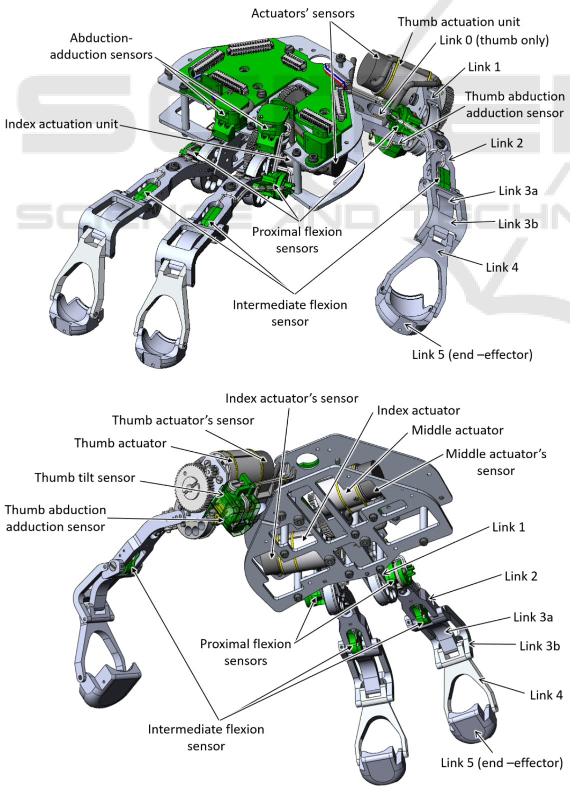

Figure 7: Main components of the master glove (top and bottom views).

3.2 Kinematics

The simplified kinematic model of the master glove is illustrated in Figure 8. Link 1 allows abduction-adduction while the other links allow finger flexion-extension. The links 2, 3a, 3b and 4 form an inverted parallelogram which allows the robot to remain close to the finger in its entire workspace. A pivot joint is added at the end of this structure to allow for the fingertip to rotate freely when the operator closes the hand.

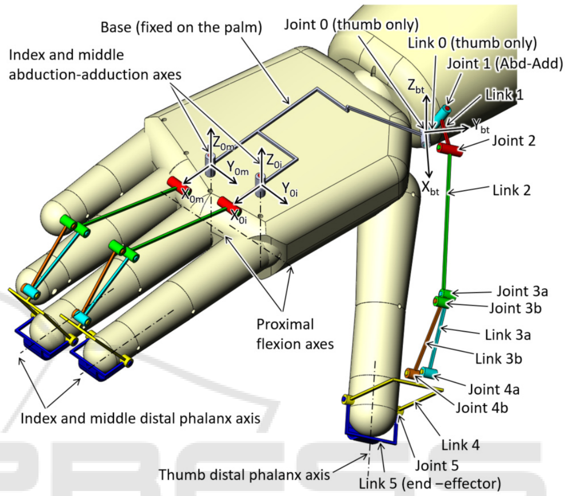

Figure 8: Kinematic model of the master glove ($R_{bt}(O_{bt},X_{bt},Y_{bt},Z_{bt})$, resp. $R_{0i}=(O_{0i},X_{0i},Y_{0i},Z_{0i})$ and $R_{0m}=(O_{0m},X_{0m},Y_{0m},Z_{0m})$ are the base frames of the thumb, index and middle fingers).

The kinematic structure of the index and middle fingers' robots is illustrated in Figure 9 (corresponding to links 1 to 5, an additional joint being added between links 0 and 1 for the thumb).

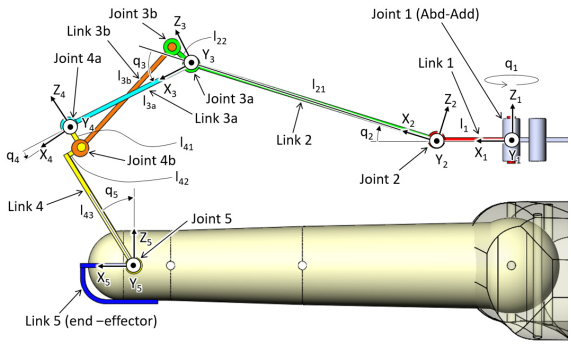

Figure 9: Kinematic model of the robots. A frame $R_i=(O_i,X_i,Y_i,Z_i)$ is associated with each link, with its origin positioned on the joint axis, q_i is the rotation around joint i, and l_i (resp. l_{i1}, l_{i2}) designates the length of link i (resp. of different parts of link i).

With these notations, the kinematic model of the index and middle robots can be written as follows:

$$T_{01}=\text{trans}(X_0,d_x).\text{trans}(Y_0,d_y).\text{rot}(Z_0,q_1) \quad (1)$$

$$T_{12}=\text{trans}(X_1,l_1).\text{rot}(Y_1,q_2) \quad (2)$$

$$T_{23}=\text{trans}(X_2,l_{21}).\text{rot}(Y_2,q_3) \quad (3)$$

$$T_{34}=\text{trans}(X_3,l_{3a}).\text{rot}(Y_3,q_4) \quad (4)$$

$$T_{45}=\text{trans}(Z_4,-l_{41}-l_{43}).\text{trans}(X_4,l_{42}).\text{rot}(Y_4,q_5) \quad (5)$$

Another transformation is required for the thumb. Equation (1) is then replaced with the following equations:

$$T_{b0}=\text{trans}(X_0,d_x).\text{trans}(Y_0,d_y).\text{trans}(Z_0,d_z).\text{rot}(Z_0,q_{zb0}).\text{rot}(X_b,q_{xb0}) \quad (6)$$

$$T_{01}=\text{trans}(Z_0,l_0).\text{rot}(Z_0,q_1) \quad (7)$$

To solve the equations of the inverted parallelogram, we use the notations illustrated in Figure 10 (Ngalé Haulin et al., 2001).

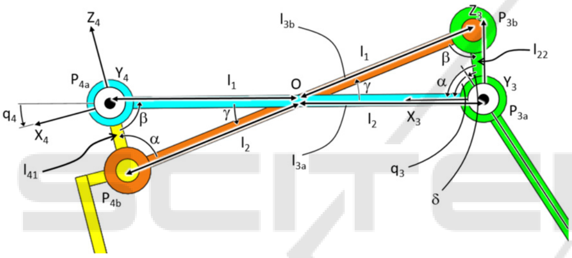

Figure 10: Inverted parallelogram.

Denoting δ the (fixed) angle between the different parts of link 2 with length l_{21} and l_{22}, we first write:

$$\alpha = q_3 + \delta \quad (8)$$

Then we use the sine formula in the triangle $OP_{3a}P_{3b}$, with O the point where links 3a and 3b cross, l_1 the distance between O and P_{3b} or P_{4a}, and l_2 the distance between O and P_{4b} or P_{3a} (here, the dimensions were chosen so that $l_{3a} = l_{3b}$ and $l_{22} = l_{41}$, hence the links 2 and 4 move in symmetry).

$$\sin(\alpha)/l_1 = \sin(\beta)/l_2 = \sin(\gamma)/l_{22} \quad (9)$$

Owing that $l_{3a} = l_{3b} = l_1+l_2$, we can write:

$$(l_{3a}-l_1).\sin(\alpha) = l_1.\sin(\beta) \quad (10)$$

$$l_1 = l_{3a}.\sin(\alpha)/(\sin(\alpha)+\sin(\beta)) \quad (11)$$

Using equation (9), we get:

$$(\sin(\alpha)+\sin(\beta))/l_{3a} = \sin(\gamma)/l_{22} = \sin(\pi-\alpha-\beta)/l_{22} = \sin(\alpha+\beta)/l_{22} = (\sin(\alpha).\cos(\beta)+\cos(\alpha).\sin(\beta))/l_{22} \quad (12)$$

By denoting $t = \tan(\beta/2)$, we get:

$$(l_{22}/l_{3a}).(\sin(\alpha)+2t/(1+t^2)) = (\sin(\alpha).(1-t^2)/(1+t^2)+\cos(\alpha).2t/(1+t^2)) \quad (13)$$

Equation (13) can be rewritten as a second order polynomial function of t as follows:

$$[(1+l_{22}/l_{3a}).\sin(\alpha)].t^2+[2.(l_{22}/l_{3a}-\cos(\alpha))].t +(l_{22}/l_{3a}-1).\sin(\alpha) = 0 \quad (14)$$

Hence we finally get:

$$\Delta = (l_{22}/l_{3a}-\cos(\alpha))^2-((l_{22}/l_{3a})^2-1).\sin^2(\alpha) \quad (15)$$

$$t = (\cos(\alpha)-l_{22}/l_{3a}+\sqrt{\Delta}) / (1+l_{22}/l_{3a}).\sin(\alpha) \quad (16)$$

$$\beta = 2.\tan^{-1}(t) \quad (17)$$

$$q_4 = \pi/2-\beta \quad (18)$$

These equations allow computing q_4 from q_3 (using equation (8) to compute α from q_3). The position of the fingertip can then be computed from q_1, q_2, q_3 and q_4.

The design of the base plate, links dimensions and joints' range of motion were optimized in order to allow free movements of the fingers over their entire workspace. It is worth mentioning that, unlike gloves and exoskeletons whose dimensions fit specific users, fingertip devices can accommodate different hand sizes. Our device can therefore easily be used by various users.

3.3 Actuation Units

As shown in Figure 11, force feedback is obtained with a Maxon REmax21 221028 DC motor (12V, continuous torque 6.07mNm, peak torque 17.3mNm (Maxon, 2016)) associated with a two stages reducer combining:

- a gear reducer with Delrin gears of 0.5 modulus allowing to obtain a reduction ratio of 5 (10 teeth primary gear HPC ZG0.5-10 glued on the motor axis, 50 teeth secondary gear HPC ZG0.5-50 as output),
- a miniature cable capstan reducer making use of a Berkley Whiplash Pro 0.42mm Dyneema cable attached to pulleys of diameter 2.3mm and 25.9mm, hence a ratio of 11.26.

Such combination is highly transparent and backdriveable, yet compact and light. It ensures that, even if backlash occurs in the gear reducer, its amplitude is downscaled at the output of the cable capstan reducer, making if almost negligible in practice. It allows generating a continuous joint

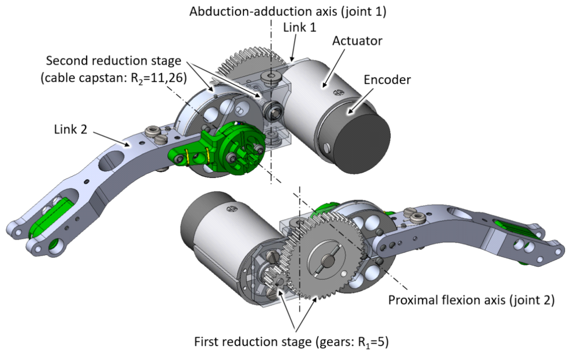

Figure 11: Actuation units.

torque equal to 0.342Nm and a peak joint torque of 0.974Nm on the proximal flexion joint.

As shown in Figure 12, the joint torque generates a force on the distal phalanx whose amplitude and direction depend on the finger configuration. Force is almost normal to the pulp when the finger is straight. The distance between the actuated axis and the fingertip being about 78.8mm in this configuration for an adult man of medium size, continuous force is equal to 4.3N and peak force to 12.4N.

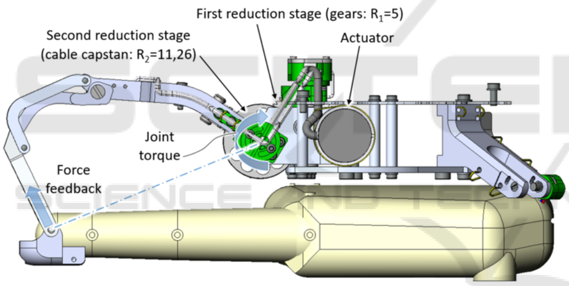

Figure 12: Force feedback generated on fingertips.

3.4 Sensors

The motors are equipped with 512ppt magneto-optical encoders (ref. Maxon MR 201940). A resolution of 2048ppt is obtained after interpolation.

Hall effect sensors with a resolution of 1024ppt are added at the joint level on the abduction-adduction axis and on the proximal and intermediate flexion axes (ref. sensors RLS RM08 VB 00 10 B02 L2 G00, ref. magnets RMM44 A3 A00).

One can notice that the measurement of the proximal flexion is redundant. It is worth noting that both sensors are however not used for the same purposes.

- Owing the reduction ratio, the motor encoders give a very precise information, and they are co-located with the actuators. They are used for the position and force control (master and slave hands are linked using a bilateral position coupling scheme). However, these sensors do not allow to know the system configuration at start-up (these sensors are incremental).
- The role of the joint sensors is precisely to give an absolute joint angle value, avoiding the need for initialization when the glove is turned on.

4 MANUFACTURING AND INTEGRATION

4.1 Dexterous Hand Master Prototype

Figures 13 below shows the manufactured prototype made of aluminium parts.

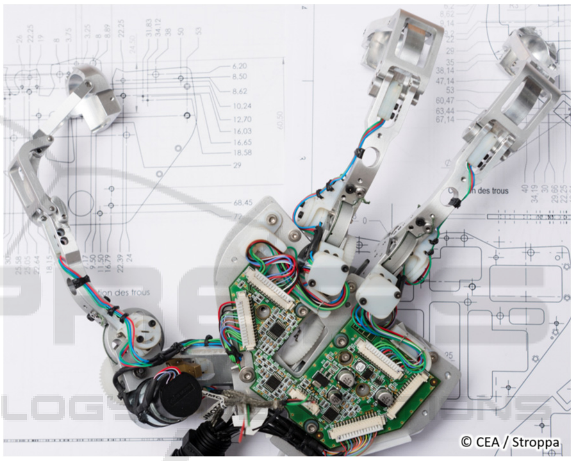

Figure 13: Internal view of the manufactured prototype of tri-digital dexterous hand master.

As shown on Figure 14, a special care was given to the actuators and sensors cables routing. Cables are guided along the robots' structure so that they cross the joints' axes. This way, they resist as less as possible to links' movements.

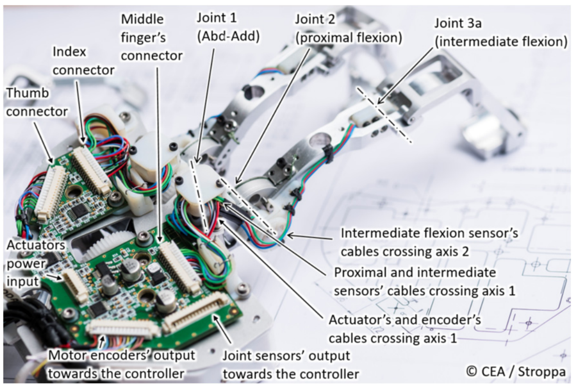

Figure 14: Dexterous hand master internal cabling.

A custom designed PCB, integrated in the base plate, is used to connect the glove to its controller. This PCB is in charge of both powering the sensors and actuators and of conditioning and filtering the sensors' signals. In order to favor modularity, each finger is connected to this PCB through a specific connector on the robots' side, and three connectors are used on the controller side, respectively in charge of the actuators power supply, motors' encoders and joint sensors.

As shown on Figure 15, this PCB is protected by a thin plastic sheet, and the base is attached to a mitten through a custom 3D printed part. This way, the glove can be easily put on or taken off.

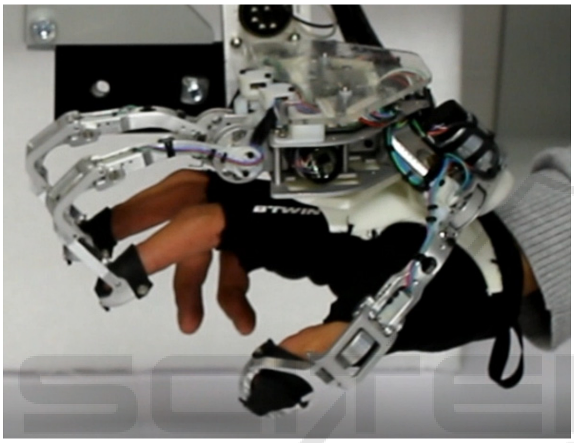

Figure 15: Fully integrated dexterous master glove.

4.2 Controller

The haptic master glove is controlled using an Ethercat controller illustrated in Figure 16. Three Maxon EPOS4 Compact 24/1.5 modules are used for controlling the actuators, while a Beckhoff EK1828 Ethercat Coupler connected to two Beckhoff EL 3068 analog input modules with 8 channels each (0-10V, 12 bits) is used to connect the joint sensors. The

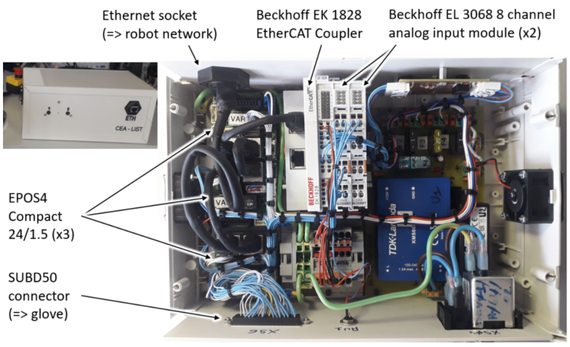

Figure 16: Dexterous hand master controller.

controller also integrates 12V (for the EPOS4 modules) and 24V (for the Beckhoff modules and the glove PCB) power supplies. It is connected to the glove through a SUBD 50 connector and to the robot network through an Ethernet socket.

4.3 Master Glove-Slave Hand Coupling

To validate its ability to remotely control a dexterous robot hand, our tri-digital hand master was coupled to the three fingers robot hand presented in section 2.1.1 using the TAO framework (Geffard et al., 2010; Geffard et al., 2012). TAO is a teleoperation middleware allowing high-speed synchronization between several real or virtual mechanisms (e.g. master arms, slave arms, dynamic simulation engine). It can control several robots synchronously, allowing master-slave bilateral position coupling with force feedback (control laws can be implemented either in joint space or in Cartesian space). First tests consisted in verifying that the slave hand can be controlled by

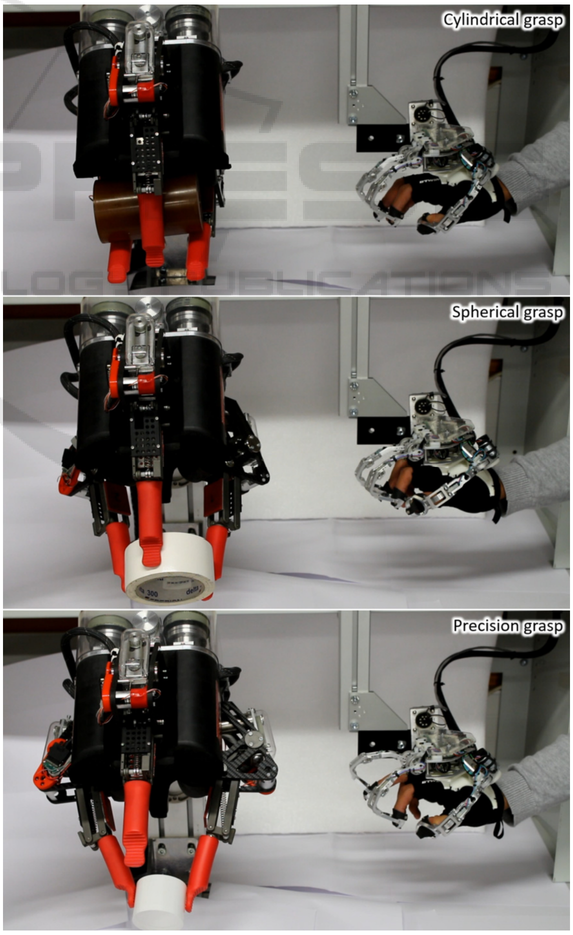

Figure 17: Dexterous teleoperation with force feedback using the tri-digital hand master.

moving the master glove, and reversely that the master hand reproduces the slave hand's motions. Finally, the master glove was used to remotely grasp various object with force feedback (see Figure 17).

4.4 Bi-manual Teleoperation

Once validated, the master hand glove was mounted on a Haption Virtuose 6D master arm, in order to allow controlling both a slave robot and the slave hand. It was further associated with a second master slave system as specified in section 2.1.2.

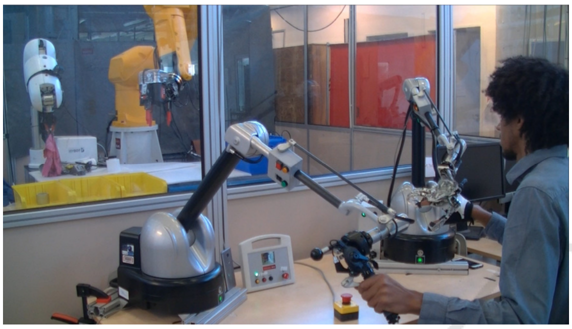

Figure 18: Bi-manual dexterous teleoperation.

First evaluations were essentially functional. We tested the ability of the operator to grasp and manipulate several types of objects similar to the waste found in nuclear containers (e.g. piece of cloth, rigid objects, cables, etc.). As shown in Figure 18 and Figure 19, these operations were successful. It was even possible to pass objects from one robot to the other.

Further details on the coupling schemes and qualitative and quantitative evaluations will be given in a coming paper.

Figure 19: Grasping various objects in teleoperation.

5 CONCLUSIONS AND PERSPECTIVES

This paper presents the specifications and design of a novel tri-digital dexterous master glove developed for the sorting and segregation of nuclear waste. This master glove is composed of a base plate fixed on the palm and three robots allowing tracking and applying force feedback on the thumb, index and middle fingertips. Thanks to its optimized design, it can span the entire workspace of the fingers, and its high-performance actuation allows for a good quality force feedback. After validating that it can be used to control a three fingers slave hand with force feedback, it was successfully integrated in a bi-manual dexterous teleoperation set-up, allowing to grasp and manipulate various kinds of objects. Further details on the coupling schemes and evaluations will be given in a coming paper. Future work should be dedicated to a more precise experimental characterization of the device performances.

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