SMARTsurg

SMart weArable Robotic Teleoperated surgery

D3.4: Wearable surgical system demonstration

Due date: M18

Abstract: The present document is a deliverable of the SMARTsurg project, funded by the European Commission's Directorate-General for Research and Innovation (DG RTD), under its Horizon 2020 Research and innovation programme (H2020). This report describes the work on the wearable surgical system and its attachment to the haptic master device. The progress has been made from our initial exoskeleton prototype at the start of SMARTsurg project. Improvements are required in terms of the motion tracking accuracy, usability and modularity of the exoskeleton. Three different designs have been created and tested in laboratory, taking into account users' requirements and feedback. Attachment of the hand to the master device that does not obstruct or impede the user's movements has also been included in this report.

Dissemination Level		
PU	Public	x
PP	Restricted to other programme participants (including the Commission Services)	
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D3.4: Report on wearable system development

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Document Change Log

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Change Log	Version	Date
First draft	0.1	June 25, 2018
Second draft	0.2	June 25, 2018
Third draft	0.3	June 29, 2018

D3.4: Report on wearable system development

Table of Contents

Contents

Executive Summary

For Task 3.4, as defined in the GA, we have been investigating a wearable hand system (a.k.a. exoskeleton) for real-time tracking of the movements of the hand digits and wrist. This system includes improvements in ergonomics and weight as well as adjustability for various users and hand sizes. The exoskeleton will be integrated via a simple attachment with a commercial haptic arm (Haption Virtuose 6d Desktop) which will also track movement of the user’s forearm.

This task has been considered using the surgical requirements elicited in WP2 and reported in D2.1 and D2.2.

Three exoskeleton designs and the master device interface design are presented in this report that will be subsequently tested for accuracy and repeatability in laboratory environment and usability with surgeons of different specialties.
This is an interim report and a full version of this deliverable will be submitted in M28.

1. Introduction

1.1 Objective and Scope

This deliverable (D 3.4 – “Wearable surgical system demonstration”) reports the Smartsurg project progress on the development of the surgeon’s hand motion tracking during teleoperation of surgical instruments. Master console requirements have been elicited at the first stage of the project and reported in D2.1 and D2.2. This development started from our initial hand exoskeleton design with the view to optimise its usability, ergonomics, degrees of freedom, interface with the master haptic device and mapping with the anthropomorphic instrument design.

1.2 Document Structure

The document starts with a brief overview of surgical master devices followed by the surgical requirements elicited in the first 8 months of SMARTsurg project which formed the basis of all subsequent development. This is then followed by a brief description of pre-SMARTsurg work on hand master interfaces that SMARTsurg developments are based on, as well as the hand kinematic model.
Sections 3 to 5 present our work on the development of various wearable hand master prototypes and interface. Section 6 presents conclusions from the current work and plans for the next 12 months.

1.3 Acronyms and Abbreviations

Abbreviation	Definition
RAMIS	Robot-assisted minimally invasive surgery
IMU	Inertial measurement unit
DOF	Degree(s) of freedom
CAD	Computer aided design
PCB	Printed circuit board

2. Robotic surgery teleoperation

Robotic teleoperation systems consist of two main sub-systems – the master console, directly controlled by the surgeon and the slave side which comprises a robot connected to a surgical instrument. The key aspect of the master side is to provide transparency by tracking the surgeon's hand motion precisely and allowing for unimpaired perception of interaction forces. Trade-off between transparency and stability, determined by master control of the slave side, has to be made in order to create an effective teleoperated system.

2.1 Overview of surgical master devices

Master devices for hand motion tracking are on-the-hand hardware, based on rigid links and encoders that track digit joints [1], or use external imaging systems [2] to track the hand/finger poses and require intensive image processing. Hand based hardware can be heavy and restrictive to the operator's hand in prolonged use, and image-based systems are susceptible to environment lighting.
Other low-cost sensors, such as Leap Motion have been frequently used for body, arm or hand tracking. Leap Motion has sub-millimetre accuracy [3] and has been used as a user controller for manipulating virtual bone fragments [4]. While such devices avoid burdening of the hand with extra load, they usually are challenged by occlusions resulting from overlapping fingers and/or flexion of the wrist. Vision systems also depend on environment lighting and this can be problematic for surgical application.
Both these approaches cannot support integration of haptic feedback which is one of the main prerequisites for the development of SMARTsurg system. Many studies have investigated the complex relationship between the user and the master device in the effort to improve the time required to acquire teleoperation skills and provide more natural control of the slave side.

2.2 Master device requirements for Smartsurg use cases

Hand Exoskeleton has been stated as the preferred master device for majority of the interviewed surgeons - (43%) for Orthopaedics, (40%) for Urology, Cardio surgery (45%). A spectrum of other devices like Omni Phantom, Leap motions, etc. scored much lower.

Specific features of the master exoskeleton are following:

- one hand exoskeleton integrated with Virtuose 6d Desktop for each hand
- lightweight
- adjustable for various hand sizes
- compact (including interface with Virtuose)
- fewer wires
- integrated with haptic feedback

2.3 Kinematic model of the hand digits and wrist

Examining the joints of the human hand and constructing a kinematic model is instrumental in understanding the specifics of its movement. Table 1 describes the model that is used for each of the three hand digits (thumb, index and middle fingers) that are tracked by the master (hand exoskeleton). In addition to these, we consider the wrist to have 3 DOF, resulting in 16 DOF in total for each hand. The resulting simulated hand, with a Table describing the Denavit Hartenberg parameters for the digits are given in Appendix I.

Table 1: Model of the human hand digits

Digits	Type of joint	DOFs
Index and middle	distal interphalangeal (DIP)	1
	proximal interphalangeal (PIP)	1
	metacarpophalangeal (MCP)	2
Thumb	interphalangeal (IP)	1
	metacarpophalangeal (MCP)	1
	Carpometacarpal (CMC)	3

2.4 Pre-SMARTsurg exoskeleton

The SMARTsurg master system is based on the previously developed hand exoskeleton in Figure 1 [5, 6], which comprises 19 1-DOF Hall-effect sensors (Melexis[1], Belgium) that measure digit joint angles. Each joint is measured by one sensor apart from the MCP joints of the index and middle fingers and the CMC of the thumb, for which flexion is measured by 3 sensors in the three-bar mechanism shown in Figure 2, using equation (1):

$$MCP = 90 + \theta_1 - \theta_2 - \theta_3 \tag{1}$$

[1] https://www.melexis.com/en/product/MLX90316/Absolute-Rotary-Position-Sensor-IC

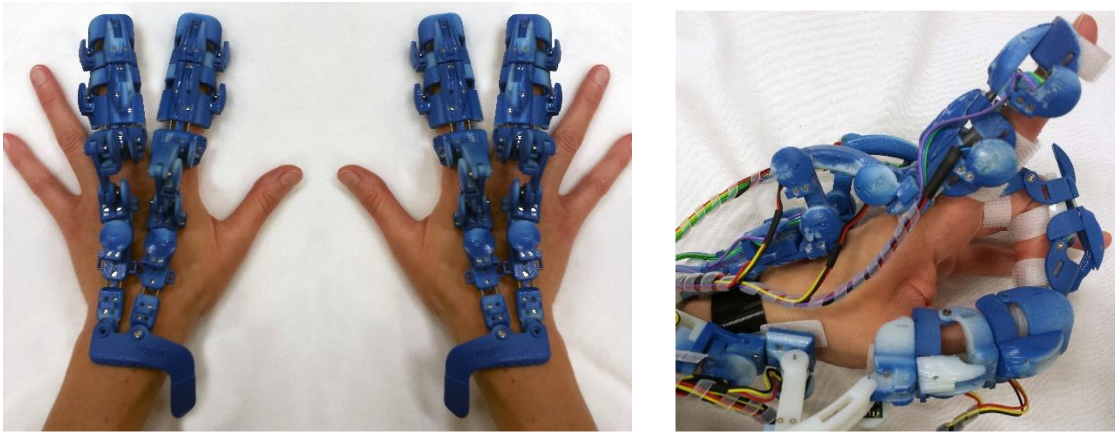


Figure 1: BRL μAngelo hand exoskeleton

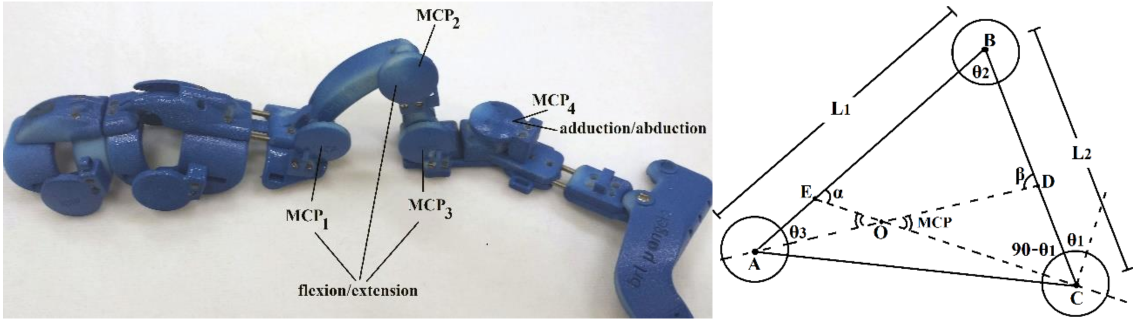


Figure 2: Calculation of the MCP joint angle from three sensor measurements

This exoskeleton, weighing 200gr including electronics, is adjustable to different digit lengths and can capture motion of the three digits accurately with the sensors' resolution being as low as 0.02 degrees. It also is repeatable with an error in the order of μm in digit abduction/adduction. However, the pronation/supination of the thumb's CMC joint is not successfully tracked due to the design that places the corresponding sensor in a sub-optimal position. Furthermore, the mechanism shown in Figure 2 can be difficult to fit and fix on the user's hand, resulting in MCP joints errors of the index and middle fingers.

3. SMARTsurg master devices

The proposed improvement on the pre-SMARTsurg exoskeleton design is:

“A hand exoskeleton for better tissue manipulation and grasping and an extended multi-DOF shaft for better dexterity inside the abdomen interfaced with Haption Virtuose 6D desktop, and Cybernetix Real Time 3D supervision software managing the haptic force-feedback between the slave and the master exoskeleton.”

3.1 Rigid/soft hybrid exoskeleton

To reduce the exoskeleton weight and make it more compact and ergonomic, each of the 3-sensor mechanisms shown in Figure 2 were replaced by 2 IMUs (Inertial Measurement Units) (BNO55[2], Bosch), while an additional IMU is used for wrist tracking. This design comprises a total of 5 Hall-effect sensors and 5 IMUs to track 16 DOF of the user’s hand and is shown in Figures 3 and 4.

The CAD files (see Appendix II) are parametric so that once the user’s digits measurements are taken the design can be adjusted and all the parts can be fast 3D printed. Furthermore, the middle link of each digit is adjustable for fine tuning of the size. The sensors are transferable between the exoskeleton versions but require careful calibration: the Hall-effect sensors need to be calibrated once after installation in the new exoskeleton and the IMUs need calibration before each use.

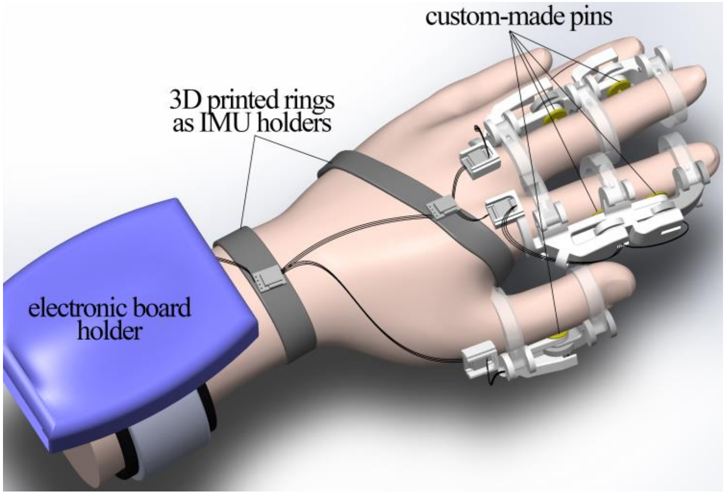


Figure 3: envisioned concept with rigid parts and flexible straps comprising 2 types of sensors

A custom-made motherboard (Figure 4) was designed for sensors data acquisition (see Appendix III for schematics), while it also has provision for a 6th IMU as a redundant sensor for the intricate CMC joint of the thumb.

The rigid parts of the exoskeleton were printed in Verowhite (Stratasys, USA) and the soft straps in TangoPlus, TangoBlackPlus or Agilus30 (Stratasys, USA). In the current prototype, the electronics board is held on the forearm with hypo-allergenic flexible tape. The total weight of the exoskeleton including 5 Hall-effect sensors, 5 IMUs and the associated electronics is 40 gr, improved from the previous prototype at 200gr.

[2] https://www.bosch-sensortec.com/bst/products/all_products/bno055

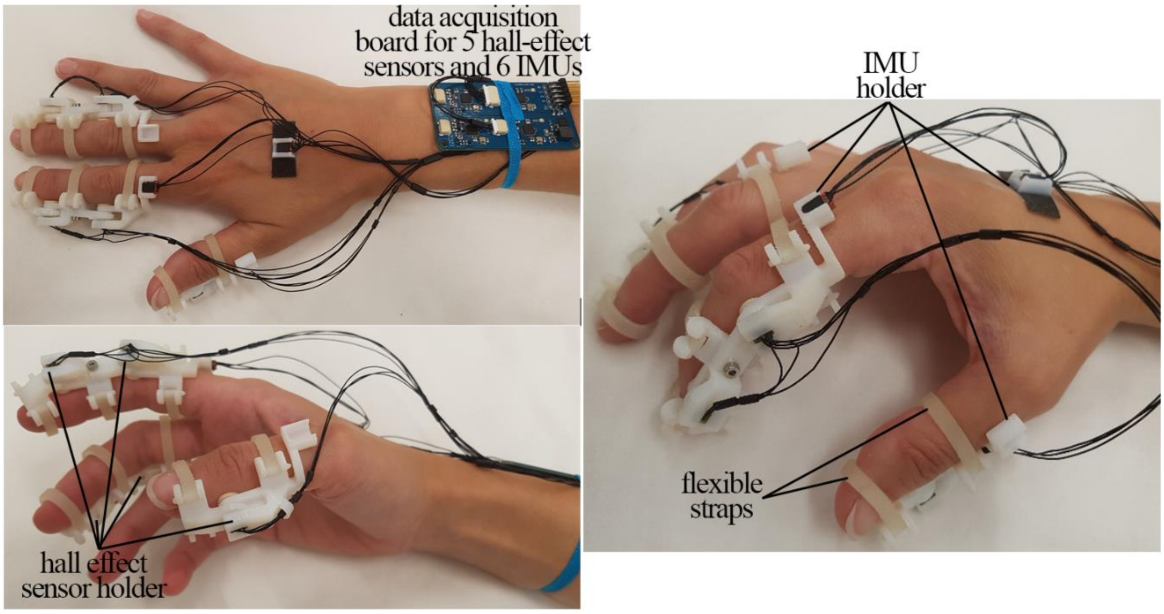


Figure 4: prototype of the hybrid soft/rigid exoskeleton with 2 types of sensors

3.2 Rigid exoskeleton

In parallel to the rigid/soft design of the previous section, a 2nd design is being developed for use exclusively with Hall-effect sensors, but with ergonomically improved design compared to the exoskeleton in Section 2.4. This exoskeleton (initial prototype shown in Figure 5) also benefits from the parametric design for different hand sizes custom fit and has the advantage of not requiring calibration before each use (due to lack of IMUs).

The CAD for this design is also given in Appendix II. The design includes two plates, one for the palm and one for the dorsal side of the hand. These are intended for holding a mechanism similar to the one described in Figure 2 and are essentially replacing the hook-and-loop fasteners of the pre-SMARTsurg design. For a comfortable but snug fit, there are soft balancing stands between the top plate and the dorsal side of the hand (see Appendix, Figure 12). Instead of 3D printed flexible straps (see Figure 4), the exoskeleton is held onto the digits via elastic fabric which is easily adjustable via a custom-made cam buckle (placed on the top of the hand).

Figure 5: initial prototype of rigid exoskeleton for use with hall-effect sensors

3.3 Thumb MCP Tracking using flex sensors on the palm

Further to the exoskeleton designs of sections 3.1 and 3.2, and to address potential problems with the CMC joint of the thumb, an alternative method for measuring change in the flexion of this joint is being developed. This includes flexible film sensors (Flexpoint, USA) that are placed inside the palm of the hand and measure change of resistance due to the change of curvature.

These sensors are housed in a modular 3D printed chain, as shown in Figure 6, which can be adjusted to various hand sizes by removing/adding parts of the chain.

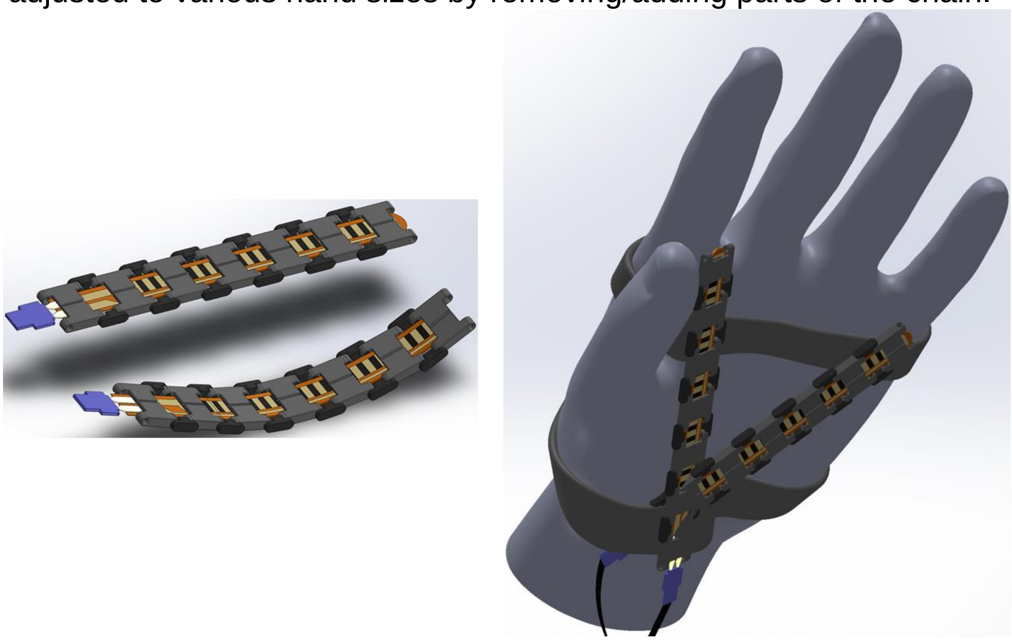


Figure 6: Flex sensor and modular 3D printed chain on the palm

4. Hand motion tracking for open surgery

In order to test and evaluate the developed instruments of WP4, we plan to carry out a case-study where we will track a surgeon's hand during open surgery on ex-vivo animal specimens. Specifically, the aim of this experiment is to investigate the range of motion and the breadth of movements of surgeons' hands during cardiac and urological surgery. Ethical approval for these experiments has been acquired, approved by the UWE Faculty of Environment & Technology Research Ethics Committee.

Experimental procedure:
The surgeon's hand will be fitted with IMUs as shown in Figure 7, tracking the position and movement of the wrist, the hand digits and joints. The system has been tested for comfort and motion obstruction of the hand while using tools.
The sensor data will be logged using the motherboard shown in Figure 7 (see Appendix III for schematics) while the surgeon is performing the simulated surgical task.
These experiments will take place in the animal specimen lab of the Bristol Robotics Lab and the participating surgeon(s) will be from the SMARTsurg consortium.

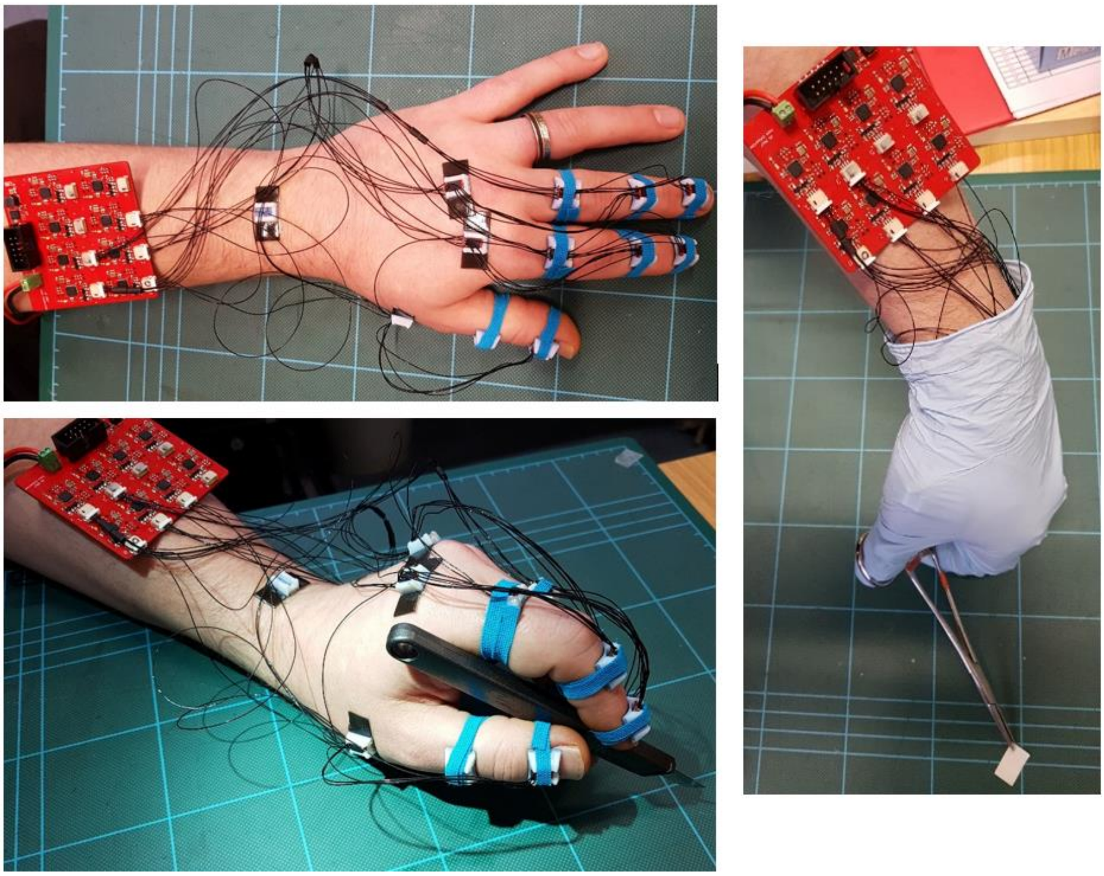


Figure 7: Hand tracking system for use during open surgery

5. Attachment between exoskeleton and Virtuose

In parallel to the development done by UWE for the exoskeleton, Cybernétix has been working on the physical interface between the master arm and the hand of the surgeon. This exoskeleton interface will allow the surgeon to plug easily onto the Virtuose Haption and feel the force feedback thanks to this rigid link. A quick connect/disconnect feature can be seen in white on the CAD model in Figure 8.

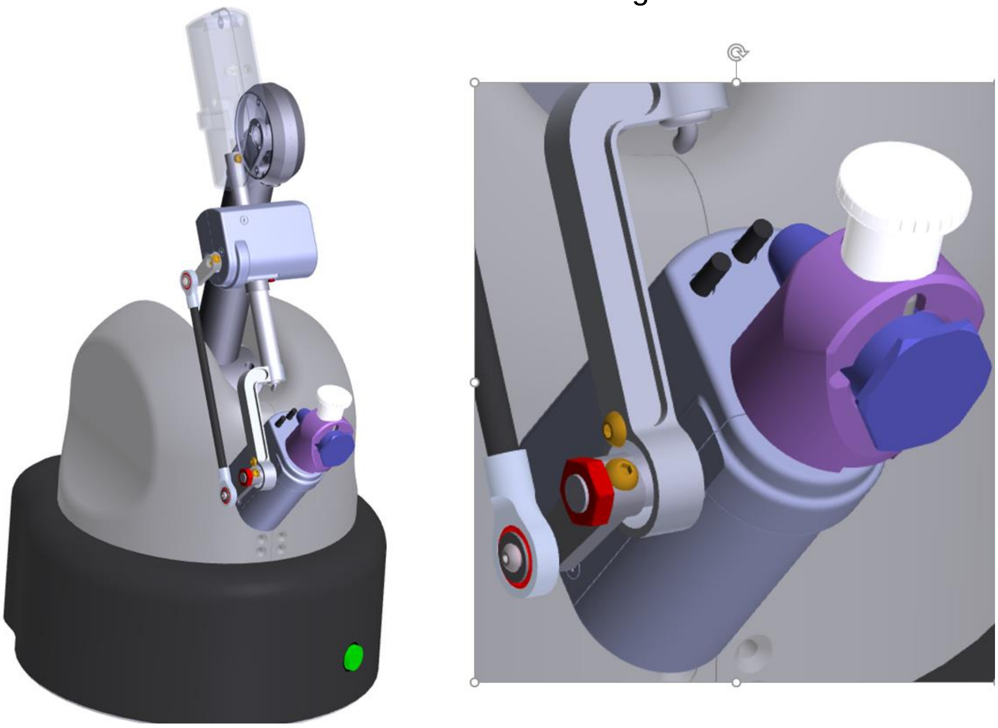


Figure 8: Attachment between exoskeleton and Virtuose in CAD

The latest version of this exoskeleton interface has been 3D printed (Figure 9) at Cybernétix. The part of the attachment on the user's hand will also accommodate the IMUs required for the finger motion tracking.
User trials have been performed by engineers and staff to criticize and evaluate the design, feeling, behaviour of this preliminary version. One critical point was to validate that the exoskeleton interface gives the surgeon a total freedom of motion and maximizes the use of the Virtuose's workspace.

Figure 9: 3D printed attachment between exoskeleton and Virtuose

6. Conclusion

This report demonstrates our joint efforts in creating a wearable interface which will act as the master of the surgical master-slave system. We have created various prototypes for the wearable system which incorporate use of one or two type of sensors. Focus has been in detailed tracking and inclusion of all joints of the hand as well as comfort and ergonomics of use while regular feedback has been sought from the surgeons of the SMARTsurg consortium in the design of these prototypes. Our further work will focus on:

- Integration of the exoskeleton with haptic feedback for palpation (detailed in report D5.3)
- Carry out accuracy tests of each prototype with simultaneous use of Polaris tracking system
- Tests in laboratory environment with lay users and surgeons using the exoskeletons and comparison between prototypes
- Map the exoskeleton to the instruments (in simulation and via physical interface)
- Tests on ex-vivo animal samples with surgeons

Future work on the attachment between exoskeleton and Virtuose will be:

- To add a layer of soft material in the inner part of the exoskeleton interface to make it more comfortable for the surgeon on the long term
- To integrate developments by both UWE and Cybernétix to finalize the overall design of the master interface

<u>References</u>

[1] Luo, H. and Wang, S. (2011). Multi-manipulation with a Metamorphic Instrumental Hand for Robot-assisted Minimally Invasive Surgery. In IEEE/ICME International Conference on Complex Medical Engineering. Harbin, China, pages 363-368.

[2] Kim, D., Hilliges, O., Izadi, S., Butler, A. D., Chen, J., Oikonomidis, I., and Olivier, P. (2012). Digits: freehand 3D interactions anywhere using a wrist-worn gloveless sensor. In Proceedings of the 25th annual ACM symposium on User interface software and technology, UIST '12. ACM, New York, NY, USA, pages 167-176.

[3] Weichert, F., Bachmann, D., Rudak, B., and Fisseler, D. (2013). Analysis of the accuracy and robustness of the leap motion controller. Sensors (Basel, Switzerland), 13(5):6380-93.

[4] Dagnino, G., Georgilas, I., Tarassoli, P., Atkins, R., and Dogramadzi, S. (2015). Intra-operative 3d imaging system for robot-assisted fracture manipulation. In Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE. IEEE, pages 9-12.

[5] Tzemanaki, A., Burton, T.M., Gillatt, D., Melhuish, C., Persad, R., Pipe, A.G. and Dogramadzi, S., 2014, August. μAngelo: A novel minimally invasive surgical system based on an anthropomorphic design. In Biomedical Robotics and Biomechatronics (2014 5th IEEE RAS & EMBS International Conference on (pp. 369-374). IEEE.

[6] Tzemanaki, A., Fracczak, L., Gillatt, D., Koupparis, A., Melhuish, C., Persad, R., Rowe, E., Pipe, A.G. and Dogramadzi, S., 2016, June. Design of a multi-DOF cable-driven mechanism of a miniature serial manipulator for robot-assisted minimally invasive surgery. In Biomedical Robotics and Biomechatronics (BioRob), 2016 6th IEEE International Conference on (pp. 55-60). IEEE.

D3.4: Report on wearable system development

APPENDICES

APPENDIX I – Kinematic parameters for the hand

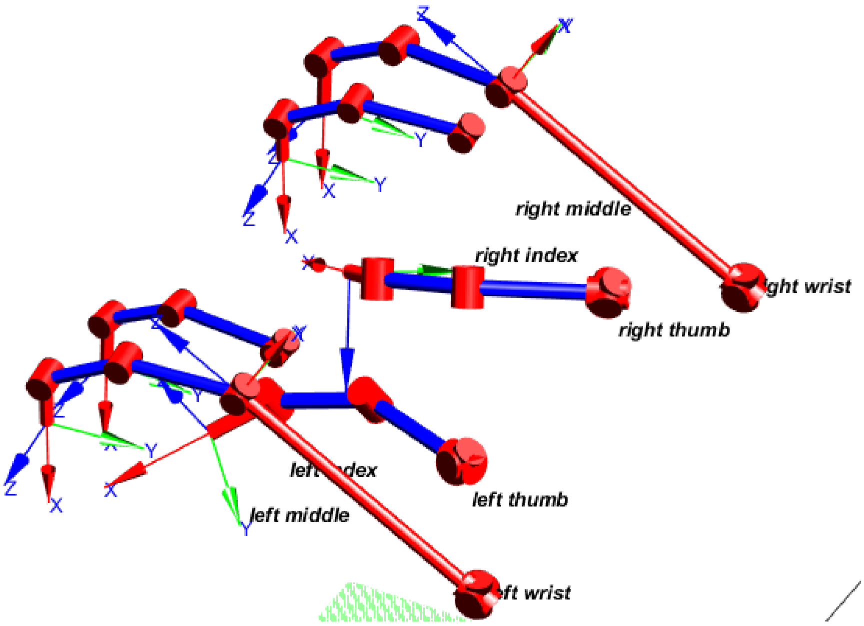


Figure 10: Simulated Left and Right hand model

Table 2: Denavit-Hartenberg parameters for 5 (thumb) and 4-DOF (index and middle) digits

4-DOF digit				
	a_i	α_i	d_i	θ_i
1	0	-90	0	θ_1
2	L_1	0	0	θ_2
3	L_2	0	0	θ_3
4	L_3	0	0	θ_4

5-DOF digit				
	a_i	α_i	d_i	θ_i
1	0	-90	0	θ_1
2	0	-90	0	q_2-90
3	0	90	L_1	θ_3
4	L_2	0	0	q_4-90
5	L_3	0	0	θ_5

APPENDIX II – CAD drawings of the designs

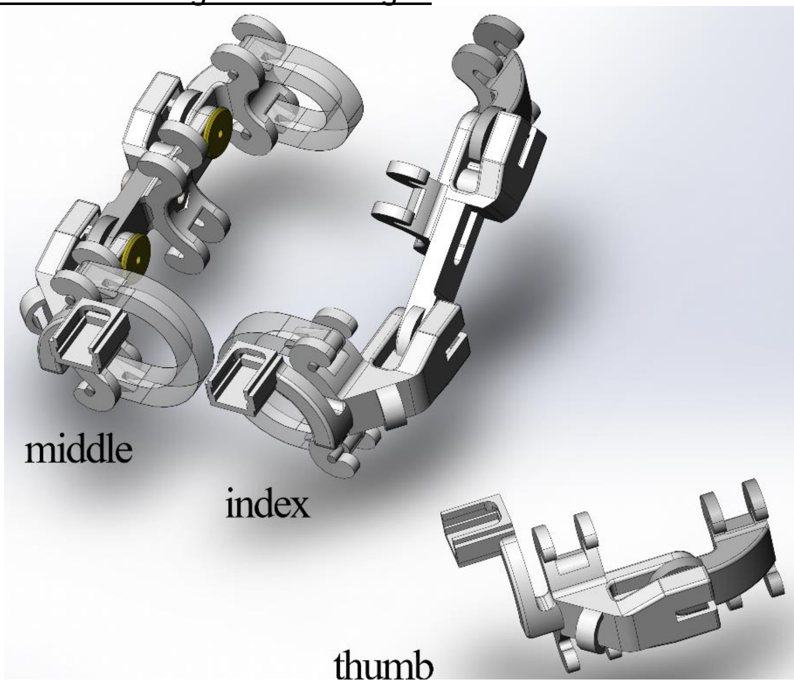
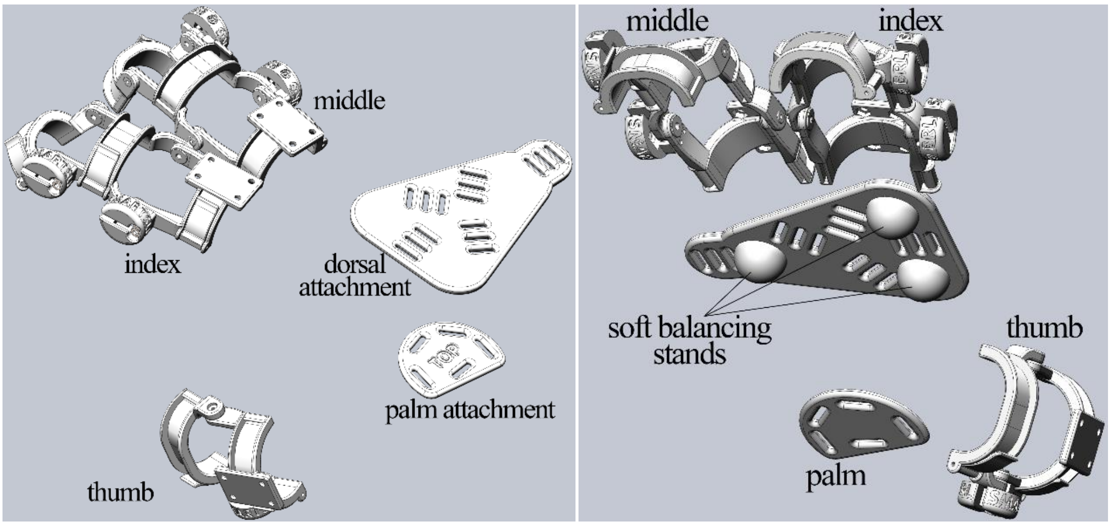


Figure 11: Rigid/soft hybrid exoskeleton

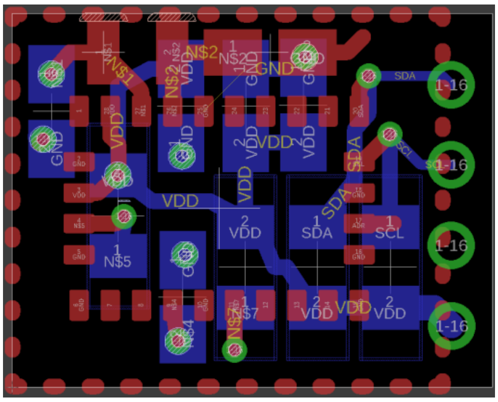


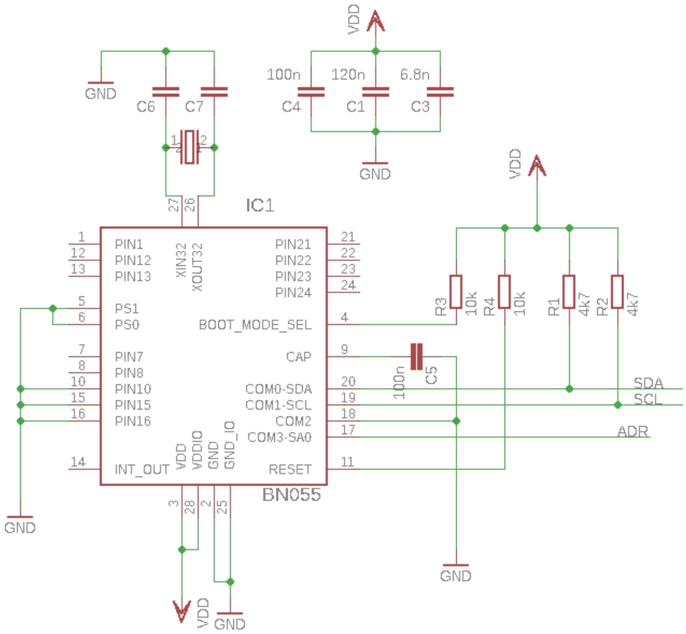
Top view bottom view

Figure 12: Rigid hybrid exoskeleton

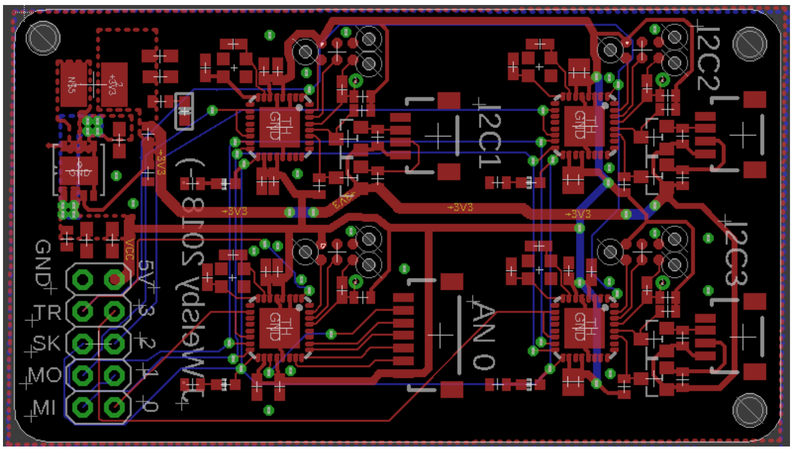
D3.4: Report on wearable system development

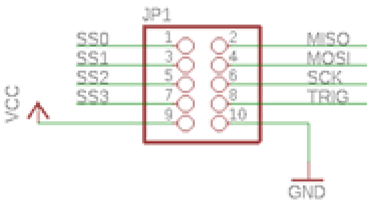
APPENDIX III – PCB designs

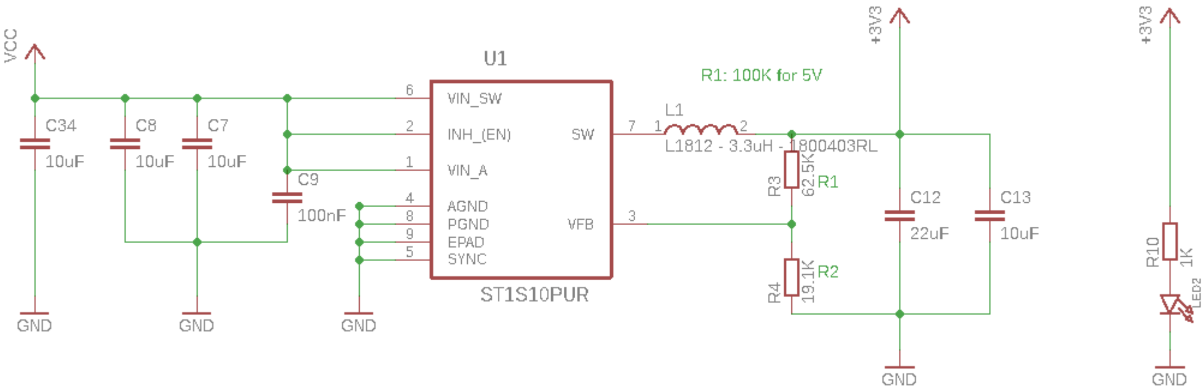




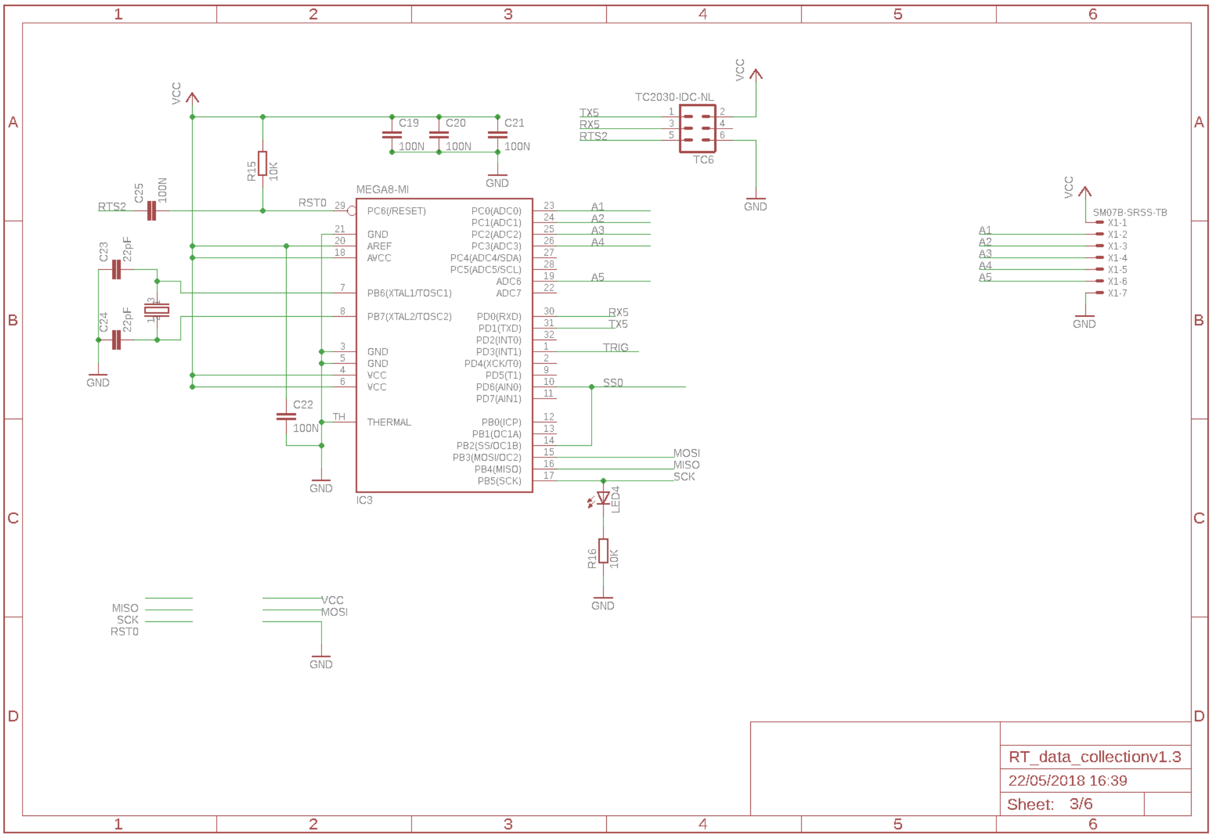
Data acquisition board for IMUs and hall effect sensors via SPI master-slave connection:

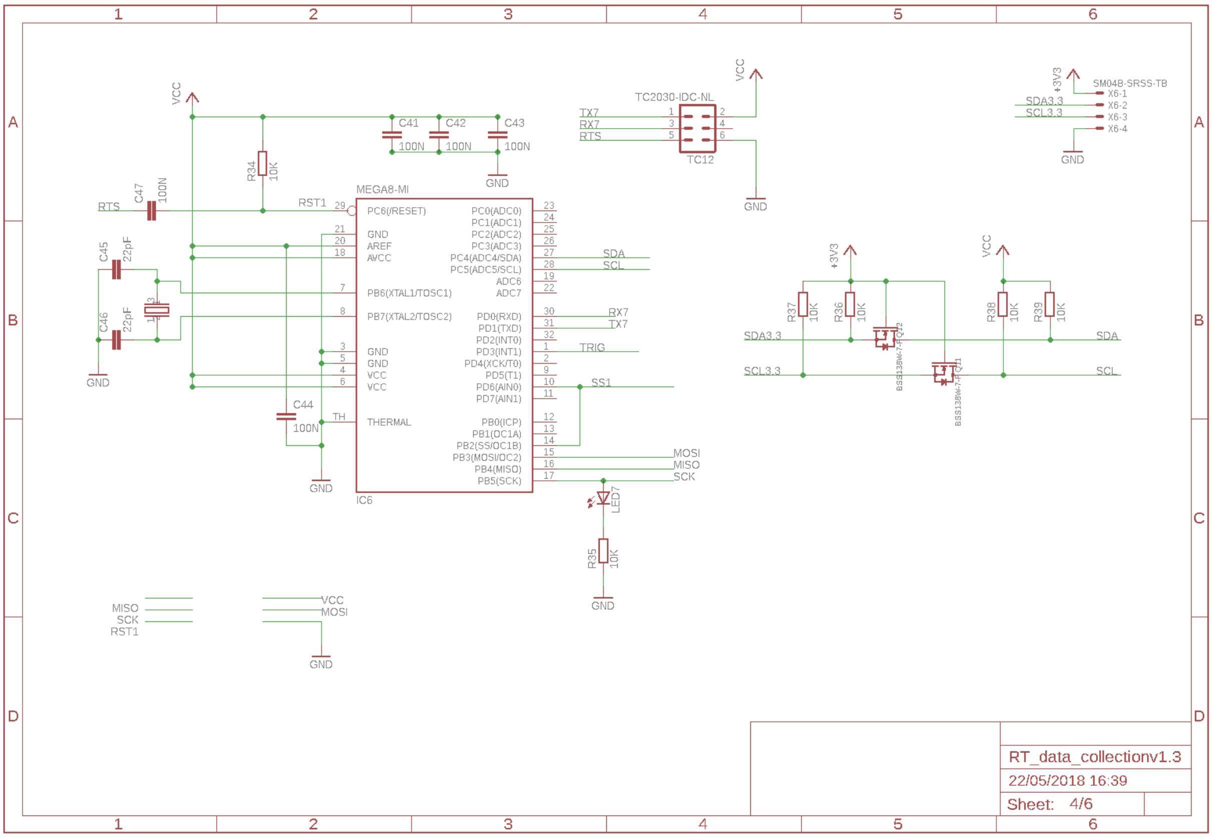






D3.4: Report on wearable system development





D3.4: Report on wearable system development

Motherboard for logging data from IMUs: