On the design of lightweight compliant wearable arms

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***Abstract*— Supernumerary wearable robotic limbs (SRL) are robotic arms that can act as co-workers for a user that wear an harness on which they are attached. The design of this class of robot is highly challenging because: 1) lightweightness is extremely important since a user bear all the weight and 2) they must be designed for safe interaction with human user. Existing SRL devices use highly geared electric motor to meet the stringent force-density requirement, this leads to highly limited performance in terms of motion velocity and control of the interaction force. Alternative designs are necessary for enabling many applications that require speed and fine control of the interaction force. Here a design approach leveraging low-intrinsic impedance actuators and transmission is explored. The approach is based on magnetorheological clutch acting on low-friction hydraulic transmission. Two prototypes are presented; design choices and performance are discussed.**

I. INTRODUCTION

Supernumerary robotic limbs (SRL) are robotic arms that can help you do things that would be uncomfortable, dangerous or impossible to do on your own. The concept is to augment the number of limbs of a user, with artificial ones that are attached to a harness, see Fig. 3. One example of application is automatic machining operation where the arm could position a tool with more accuracy than a human could, see Fig. 1. Another example application is assembly tasks where workers could use an extra hand to hold a panel while they use their own hands to perform a fastening task, see Fig. 3b. There are many other possible roles for those extra limbs: bracing the user for more stability and improved ergonomics, demonstration with a remote user teleoperating the extra arms, fall prevention with automatic canes, etc.

The design of SRL robotic devices is highly challenging mainly because of the following requirements:

1) **Mass:** The weight of the device must be very low not to burden the user that wears it;
2) **Mass distribution:** The mass of the device must be mostly located close to the user hips ;
3) **Maximum velocity:** To be capable of following and compensating human motion, actuators needs to be fast compare to traditional actuators;
4) **Compliant actuation:** To allow the control of the interaction force, actuators needs to be backdrivable and force-controllable;

Fig. 1. Worker wearing a SRL for automatic machining operation

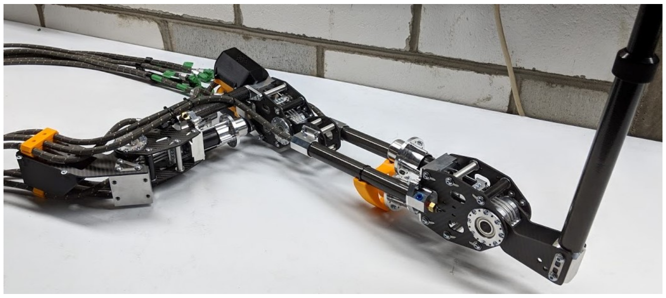

Fig. 2. Last generation prototype SRL developed at University of Sherbrooke

A. State-of-the-art of Wearable Robotic Technologies

The idea of augmenting human capabilities with exoskeleton has been explored since the 1950s. Supernumerary robotic limbs is new paradigm opening numerous new possibilities of methods for assisting the user. Fig. 4 illustrates different types of modern wearable robotic technologies. **Exoskeletons** are robotic links surrounding the human body to increase the force and/or the endurance capabilities. While state-of-the-art exoskeletons can make human lift heavier payload, most devices are cumbersome and have yet to demonstrate significant improvements to worker efficiency in real-life setting. Limitations are due to heavy actuation and power-system, and the complexity required to match the kinematics of the human body [8]. **Passive gravity**

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(a) Marvel's Dr. Octopus (fiction work) (b) First prototype developed at University of Sherbrooke in the context of a manufacturing application

Fig. 3. Supernumerary robotics limbs are robot arms mounted on a human wearer.


(a) HAL exoskeleton by Cyberdyne [1] (b) Robo-Mate and Lockheed-Martin passive devices for gravity compensation [2] [3] (c) MIT supernumerary robotic limbs [4] [5] [6] [7]

Fig. 4. Different types of modern wearable robotic technologies.

compensations devices are spring loaded mechanisms that are designed to compensate for the weight of heavy tools or objects. While both exoskeletons and passive devices can augment the human strength in lifting and holding heavy items, they are limited to these functions. **Supernumerary robotics limbs** are independent robotic arms, mounted on a human to provide a robotic co-worker. While the idea has been present in fiction works such as Marvel's Dr. Octopus in Spiderman (see Fig. 3a), the engineering of such systems is of relatively recent interest. This new paradigm of wearable technologies [5] has emerged from Prof. Harry Asada's laboratory at MIT. An advantage of supernumerary robotic limbs over exoskeletons is that the mechanical design of such devices is much simpler, thus lighter, by not having to marry the kinematics of the human body. More importantly, the main advantage is their ability to move independently from the human body which open the possibility of numerous functions, for instance forming a closed-kinematic chain [9] to improve stability or accomplishing independent tasks in parallel. Initial work at MIT (Fig. 4c), focused on simple holding functions in the context of assembly tasks, i.e. a functionality similar to third hand soldering stand but at a bigger scale. However task requiring dynamical capabilities, for instance active compensation of the motion of the user hips, have yet to be explored and studied. The paper explores the design of wearable arm with the capabilities to perform dynamical tasks, as opposed to previous works where only quasi-static tasks where studied.

II. DESIGN

In this section, the mechanical choices made to fulfill the requirements for SRL are presented as well as a mathematical model of the device. The sensitivity of the design is also assessed. The design presented is the first generation SRL made in the laboratory.

A. *Mechanical design overview*

The proposed supernumerary robotic arm is an additional wearable robotic arm attached on user's hip. This 2-DOF planar third arm is powered by a MR-Hydrostatic actuator [10]. Shoulder joint is designed to deliver 39 Nm with 115° of range of motion (-57.5° to 57.5°) and elbow joint, 25 Nm with 180° of range of motion (-90° to 90° or 0° to 180° since this joint is indexable). The first link is 0.45 m long and the second link is 0.37 m long. Joint operating ranges and link lengths were adjusted to: 1) make the user head unreachable by the device for safety, 2) create a wide workspace which includes most possible positions of the user hand and 3) limit interference with the user arms.

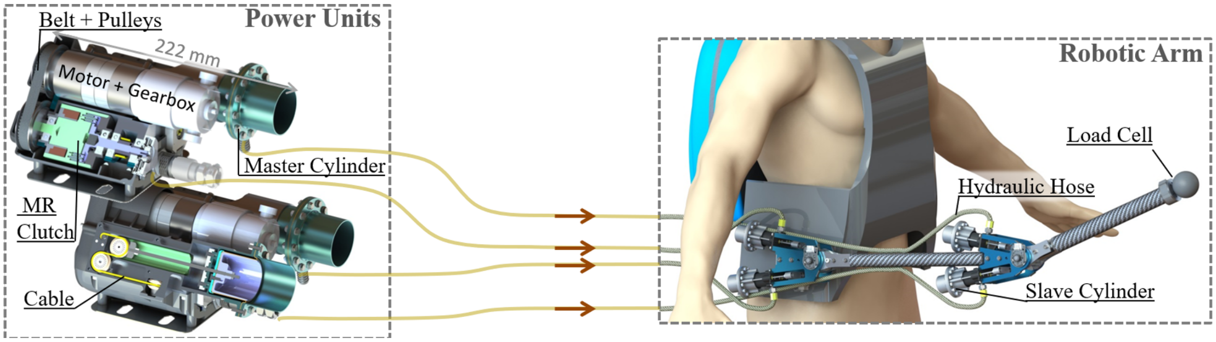

Fig. 5. Proposed SRL (first generation) worn by a user with the tethered MR-Hydrostatic power units. MR clutches vary the output torque and wind a cable that pulls the master cylinder to increase pressure. The transmission fluid is then transmitted to the robotic arm.

Principle: The whole robotic device is composed of the robotic arm and the power units (Fig.5). The power units contain a rotary power source (here, a geared electric motor), four MR clutches and four master cylinders. The output torque of the MR clutches is controlled by varying the current feeding an electromagnet controlling the magnetic field strength in the fluid. Each clutch winds a cable that pulls on a master cylinder to increase hydrostatic pressure. Resulting hydraulic flow is transmitted, through a hydraulic hose, to a slave cylinder (Fig. 6) pulling on the joint cables to rotate the robot joints (Fig. 7). Hydrostatic transmission is filled with tap water for its high bulk modulus and ease of use. Linear ball-bearings are used to guide the rolling diaphragms to avoid membrane jamming.

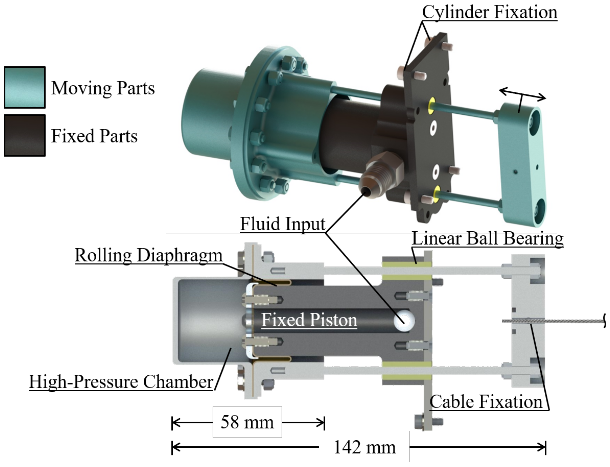

Fig. 6. Rendering of a slave cylinder used in the SRL.

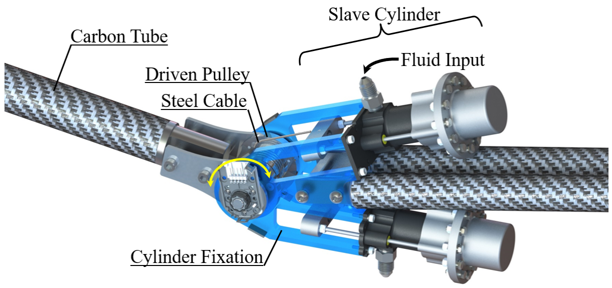

Fig. 7. Rendering of the elbow joint. Two slave cylinders mounted in an antagonist configuration and pulling on a short steel cable fixed on a driven pulley produce the rotation of the joint.

Mass: A significant advantage of the hydrostatic approach is that the power unit can be either mounted on the user's back for optimal mobility or be tethered to minimize the total weight worn by the user. Here, a tethered configuration is used and the robotic arm is located on the user's hips [11]. This location seems to be suitable to minimize the arm's total inertia perceived by the user. The use of carbon fiber tubes and custom aluminum parts allows the robot to be lightweight. When filled with water, the arm's total mass is 2.7 kg.

Backdrivability: The MR-Hydrostatic actuation system ensures a high level of backdrivability because of its low level of friction and reflected inertia [10]. First, friction in master and slave cylinders is significantly reduced by using custom-made rolling diaphragms cylinders (Fig. 6) instead of conventional cylinders [12]. Rolling diaphragm membranes roll from the bore to the piston thereby eliminating sliding motion and stick-slip friction. Second, a hydrostatic system has been chosen over a cable-driven transmission to avoid routing and cable friction issues. Hydrostatic transmission hose internal diameter and length are also chosen to minimize fluid friction and reflected fluid inertia. The hydraulic inertia is inversely proportional to the square of the internal hose diameter and directly proportional to the hose length. Third, reflected inertia is also decreased by using MR clutches since the inertia from the electric motor is not reflected to the output [13].

Maximum velocity: The maximum theoretical rotational speed of the design is 300 rpm at the elbow joint and 190 rpm at the shoulder joint when considering the nominal speed of the brushed motor. The reachable speeds highly depends on robot inertia and payload. The real maximum velocity is not assessed yet.

B. Dynamical performances

A lumped-parameter model with three internal DOFs is used to characterize the relationship from the current in the MR clutch to the interaction force with a load (see Fig. 8) for a single line. Parameters are :

- x_1: reflected translation of the MR clutch output rotor
- x_2: displacement of the hydraulic fluid
- x_3: displacement of the load
- m_1: reflected mass of the MR clutch output rotor and the master cylinder moving mass
- m_2: reflected mass of the hydraulic fluid

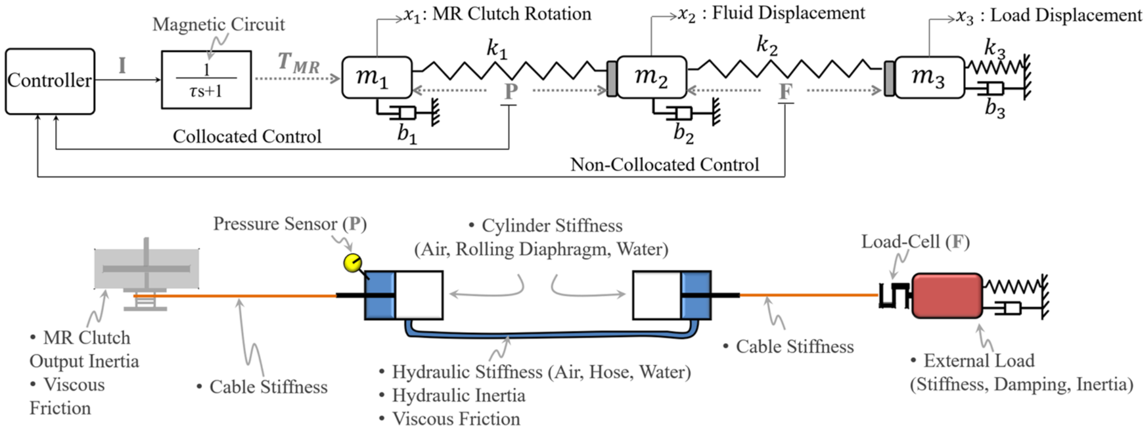

Fig. 8. One-axis lumped-parameter model of the MR-Hydrostatic actuation, from the MR clutch input current to the end effector force.

- m_3: combined mass of the output assembly, slave cylinder moving mass and external load.
- k_1 and k_2: combined compliance of the cable, membrane, water and air dissolved in water for respectively the power-unit side and the slave side.
- k_3: stiffness of the external load
- b_1, b_2 and b_3: viscous friction in the MR clutch, the hydraulic circuit, and the external load, respectively.

This model was experimentally validated to be representative of the system dynamic behavior up to a frequency range of 100 Hz, as shown in Fig. 9 and 10.

Force Bandwidth: The open-loop force-bandwidth of the actuation system is directly related to frequency response of the interaction force responding to an input current in the clutch (H_F(s)). It is analyzed for two scenarios, when the output is 1) blocked and 2) connected to a compliant load ($k_3 = 12000$ N/m, $b_3 = 20$ Ns/m and $m_3 = 1.9$ kg) that represents an environmental impedance. This impedance can be due to the compliance of the human user at the base and/or the compliance of the load at the effector side. It is found that when the output is blocked, the total system force bandwidth is 25.4 Hz, and decreases to 6.5 Hz with the compliant load (see Fig. 9 and 10). Thus, due to low intrinsic impedance of the actuator and transmission, open-loop force control can be sufficient for many situations. However, a closed-loop approach can be necessary to achieve a better control of the interaction force, especially if the impedance of the environment/human is low and if accurate force is required at end effector.

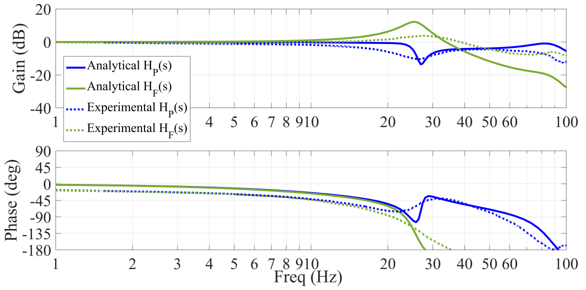

Fig. 9. Analytical and experimental Bode plots of $H_P(s)$ and $H_F(s)$ evaluated for the blocked output condition.

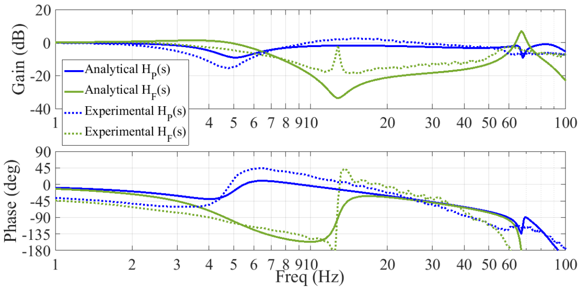

Fig. 10. Analytical and experimental Bode plots of $H_P(s)$ and $H_F(s)$ evaluated when the output is connected to a compliant load.

Sensitivity analysis: Now that the lumped-parameter model is found to be quite representative, a sensitivity analysis can be done to study the effect of design choices on dynamic performances. The effect of three parameters on the force bandwidth are analyzed: 1) the influence of the reflected rotor inertia of the actuator (MR clutch for the presented concept), 2) the influence of the transmission inertia (inertia of the hydraulic fluid for the presented concept) and 3) the influence of the transmission stiffness (compliance in the hydraulic lines for the presented concept). Tables I, II and III shows extrapolated bandwidth results based on the lumped-parameter model. A case where the compliant load is ten times heavier is also presented to assess the effect of the compliance on the results.

TABLE I

EFFECT OF THE ACTUATOR ROTOR REFLECTED INERTIA

Inertia (m_1)	Force bandwidth (-3 dB gain or -135 phase) Blocked output Hz	Compliant load Hz	0.1 x m_3 Hz
0.01x	30.3	7.8	10.5
0.1x	30.2	7.7	10.5
Baseline	**28.8**	**7.6**	**10.2**
10x	16.9	6.6	7.8
100x	5.5	2.5	2.5

Sensitivity results shows that less rotor inertia would not significantly improve dynamic performances for both blocked output or compliant output scenarios. However, concepts with much higher reflected rotor inertia would lead to worst dynamical performances. Interestingly, the presented design fall right on the corner of this performance curve.

TABLE II

EFFECT OF THE TRANSMISSION INERTIA

Inertia (m_2)	Force bandwidth (-3 dB gain or -135 phase)		
	Blocked output Hz	Compliant load Hz	0.1 x m_3 Hz
0.01x	66.6	7.2	10.7
0.1x	60.4	7.5	11.6
Baseline	**28.8**	**7.6**	**10.2**
10x	9.0	3.0	3.7
100x	2.8	1.1	1.1

TABLE III

EFFECT OF THE TRANSMISSION STIFFNESS

Stiffness (k_1 & k_2)	Force bandwidth (-3 dB gain or -135 phase)		
	Blocked output Hz	Compliant load Hz	0.1 x m_3 Hz
0.01x	1.8	1.7	1.7
0.1x	10.4	6.3	7.1
Baseline	**28.8**	**7.6**	**10.2**
10x	85.9	7.8	10.5
100x	-	7.8	10.6

The inertia of the transmission also has a big influence on the bandwidth. The transmission inertia is a bandwidth bottleneck for the blocked output case, i.e. a lighter transmission would improve performances, but not when coupled with the compliant environment. This is due to the relatively low environment dynamic behavior. However, more inertia in the transmission would deteriorate rapidly the bandwidth for both scenarios. Regarding the transmission stiffness, it is directly correlated to the force bandwidth for the blocked output case. However the transmission stiffness is not a bottleneck when coupled with the compliant environment. The performances are affected negatively if the transmission is more compliant. Interestingly, the analysis shows that some design parameters have a major influence on the bandwidth for the blocked output case but have much less impacts when evaluated for the scenario including an environmental impedance, i.e. a compliant base and/or output.

III. CONCLUSION

In this paper, a design approach featuring MR clutches and hydrostatic transmissions composed of rolling diaphragms was presented as a strategy to provide high interaction dynamics for the SRL applications. These were implemented in real 2 DOFs and 3 DOFs robotic arm prototypes. It was shown that this design allows a lightweight robotic arm (2.7 kg) with high backdrivability and open-loop force-bandwidth up to 25 Hz when blocked and 6.5 Hz when coupled to an impedance. Furthermore, a proposed mathematical model was demonstrated experimentally. A sensitivity analysis shown that some parameters have strong impacts on the bandwidth for the blocked output case but have less influence when there is a compliant load or base such as a human.

In all, the results presented in this paper suggest that the MR-Hydrostatic approach is a promising actuation technology for SRL systems. Future work is required on the influence of human impedance on performances as well as control strategies to extend bandwidth when limited by environmental impedance.

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