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Supernumerary Robotic Limbs for Aircraft Fuselage Assembly: Body Stabilization and Guidance by Bracing

Federico Parietti and H. Harry Asada, *Member, IEEE*

***Abstract*— A new type of wearable robot that assists the wearer with extra arms secured around the hips is presented. Supernumerary Robotic Limbs (SRL) can hold objects, clamp them to a fixture, guide and support human hands, and assist the wearer in performing a task as a close co-worker. This paper focuses on a class of tasks where SRL physically interacts with the environment through contact. SRL makes contact with a wall and thereby braces the human body against the environment. SRL also guides the human hands by placing a drill jig over the drilling location. Bracing the human body and guiding the hands, SRL can enhance the drilling task stability and accuracy. The SRL technology is applied to aircraft assembly, where conventional industrial robots failed to perform effectively.**

First, the basic design concept of SRL is summarized, and task strategies using SRL and their functional requirements are described. Kinematic and static properties resulting from the structural closed loops formed around the SRL, the human, and the environment are analyzed, and effective strategies for physical disturbance rejection and fine positioning are discussed. A prototype robotic arm grasps the aircraft fuselage structure. Another robotic arm places a drill jig precisely on the fuselage structure, and guides and stabilizes a hand drill held by the human user. An optimization method is developed in order to identify the SRL kinematic configuration and joint torques that stabilize the drill and at the same time minimize the human workload.

I. INTRODUCTION

Imagine that one-day humans have a third arm and a third leg attached to their body. The extra limbs will help them hold objects, support the human body, share a workload, and streamline the execution of a task. Supernumerary Robotic Limbs (SRL) secured around the hips represent one type of co-robot having an intimate relationship and highly coordinated activities with the human [1] [2] [3]. The robot-on-the-human approach has the potential to change the standard of manual labor; productivity and work quality may be improved, fatigue and injury may be reduced, and human mistakes can be minimized.

The development of SRL was motivated by the needs of the aircraft manufacturing industry. Aircraft manufacturing is largely dependent on manual labor due to the complexity of tasks, stringent inspection requirements, difficulties in installing a conveyor line, and small lot size. In a typical aircraft assembly factory, a number of scaffolds are used to assist human workers in accessing a large fuselage. Traditional industrial robots hardly fit this type of manufacturing environment that has been designed primarily for human workers. The scaffold floors are neither solid for securing robots, nor suitable for the traditional robots to move around. Special mobile platforms or long arms will be necessary to access various parts of a large fuselage and wings.

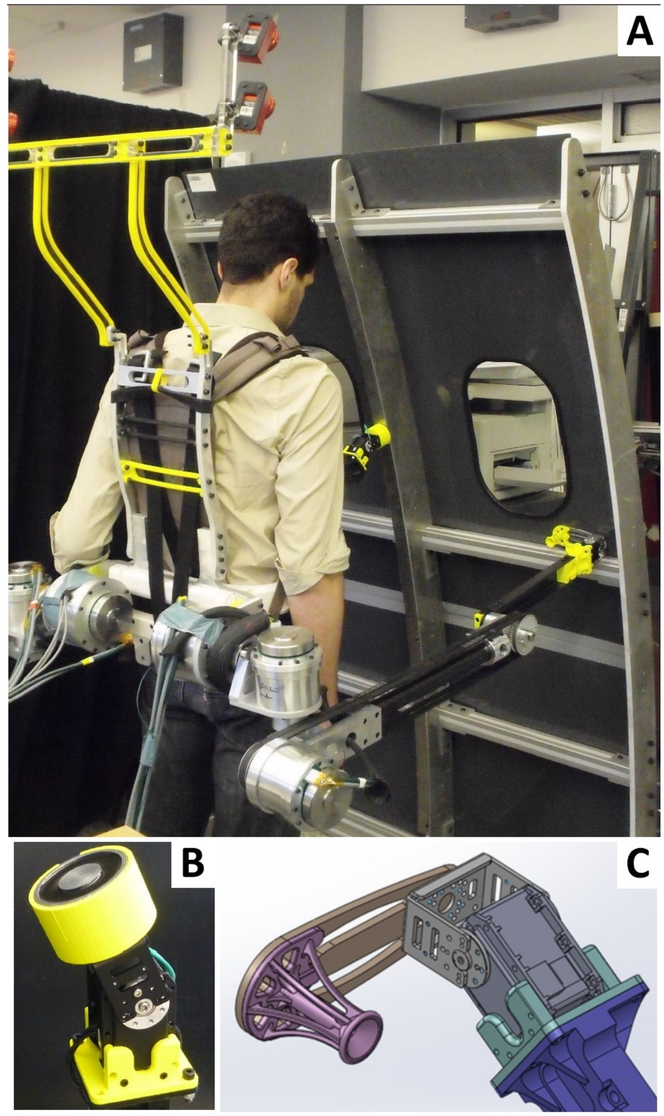

Fig. 1. A) The SRL prototype used in a drilling task. B) The electromagnet used to establish contact with the environment. C) The drill jig end effector. In the middle of the purple element there is a hole (bushing) whose function is to guide the drill bit.

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F. Parietti is with the Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA parietti at mit.edu
H. Asada is with Faculty of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA asada at mit.edu

Developing such special robots that can climb up a large aircraft body remains a technical challenge [4]. Although special mobile robots can be developed for the future, manual labor cannot be eliminated and scaffolds will remain, which may interfere with the mobile robots.

These problems in aircraft manufacturing motivated the authors to explore a new approach to bringing robots to the type of environment where a) the site is difficult for robots to access, and b) works are predominantly performed by manual labor, and are difficult to eliminate. While exploiting the superb human abilities, including mobility, flexibility, task knowledge, and manipulative skills, supernumerary robotic limbs can supplement the human's limitations and improve productivity and efficiency.

Exoskeletons have been studied for extending the human ability of muscular works since the early development at General Electric (Hardiman, 1960s) [5], and more recently extensive works have been conducted [6] [7] [8] [9]. The SRL is fundamentally different in kinematic structure and functionality. Unlike exoskeletons, the SRL has independent manipulators and extra legs that are not attached to the human arms and legs for strengthening the corresponding joints. Instead, the robotic arms branch out from the human body, and take an arbitrary configuration. Contacting various surfaces and bracing the body against a wall, rails, and the floor allow the SRL to effectively support the human body and provide a variety of function beyond load bearing.

The current work explores a promising application for the SRL's bracing functionality. The SRL can provide the human with positional references, jigs, and tools for assisting the human in executing tasks that require high accuracy or robustness to disturbances. For example, a SRL carrying a drill jig can place the jig at a desired position, guide a hand drill held by a human worker, and stabilize the drilling operation. Exploiting bracing for stabilization and guidance requires strategic task analysis and synthesis. The kinematic and static behaviors of the SRL and the human are complex, forming kinematic loops due to bracing. In the following, we will model the SRL system and formulate a task synthesis problem where the robot arm posture, bracing positions, and robot joint torques will be optimized.

II. APPLYING THE SRL TO AIRCRAFT FUSELAGE ASSEMBLY

Figure 1 shows a typical assembly task inside a large aircraft fuselage. A beam, called inter-coaster, is placed between two vertical frames, and secured with special bolts. This assembly task requires many steps of operations, including picking up a workpiece, positioning it against the fuselage frame, clamping the workpiece to the fuselage, making holes with a drill, installing bolts, and fastening the bolts. Currently, the work is executed completely by human labor. For complex installation two workers must collaborate to complete the job.

This task procedure can be streamlined with the use of the SRL. Figure 1 shows a prototype SRL system developed at the MIT d'Arbeloff Laboratory. It consists of two 4 DOF robotic limbs, a waist bracket for securing the robot around the waist, and end-effectors attached to the tip of the arms. The SRL system is equipped with a motion capture system placed above the backpack frame. One SRL may be equipped with a clamp at its end point, as shown in Figure 1, and secure the beam temporarily against the fuselage structure, rather than the human picking up and setting the clamp. Then the human can immediately move on to drilling. Another SRL can assist the human in positioning the drill against the frame. As shown in Figure 1, the second SRL may be equipped with a drilling jig at its end point, and place it precisely at a specified position by using proximity sensors at the tip or other types of sensors detecting the location of the fuselage structure. Furthermore, the drilling jig can keep the drill bit perpendicular to a beam surface and guide it to the exact location where a hole must be made. The human's work load is substantially reduced, since his/her job is simply pushing the drill towards the surface, i.e. 1 DOF motion. The SRL with the drilling jig can support the drill in other 4 DOF: x and y translations and pitch and yaw rotations.

In this example task, the first SRL clamps the beam against the fuselage structure. Note that, in turn, the human body is physically constrained by the SRL connecting the human body to the fuselage. In other words, the human body is braced against the fuselage structure. This can secure and stabilize the human body while performing the laborious task. Assembly tasks of a large aircraft fuselage are often performed in an unsecure environment with only partially covered floors. Bracing the human body will contribute to stabilizing the body and improving safety.

In the drilling task considered in this study, the SRL has two goals. The first one is to indicate the correct hole location to the user. This is achieved by placing the drill jig on the aircraft frame surface, so that its central bushing will guide the drill bit towards the desired position. Using the motion capture system and endpoint feedback control, the SRL is able to position the bushing more accurately than an unaided human worker, guaranteeing also task repeatability. The second goal of the SRL is to hold the drill jig in place during the drilling process. This anchoring phase is critical, because the bushing must be fixed to the hull surface despite the presence of several potentially large disturbing forces. The main perturbations are the human-induced disturbances (involuntary movements, postural sway, breathing), the vibrations produced by the drill, and the unwanted force components (perpendicular to the dilling axis) that the worker may generate while pushing the power drill.

Since the drill jig has no gripper, it can be anchored to the hull in only one way: by pressing it on the aircraft wall with a force which is perpendicular to the contact surface. This perpendicular force will then generate static friction components which will be able to absorb disturbances parallel to the contact surface, as long as they are within the friction cone. This drill jig anchoring strategy has several advantages: first, the robot does not need any pivots or special features to hold on to. The drill jig is

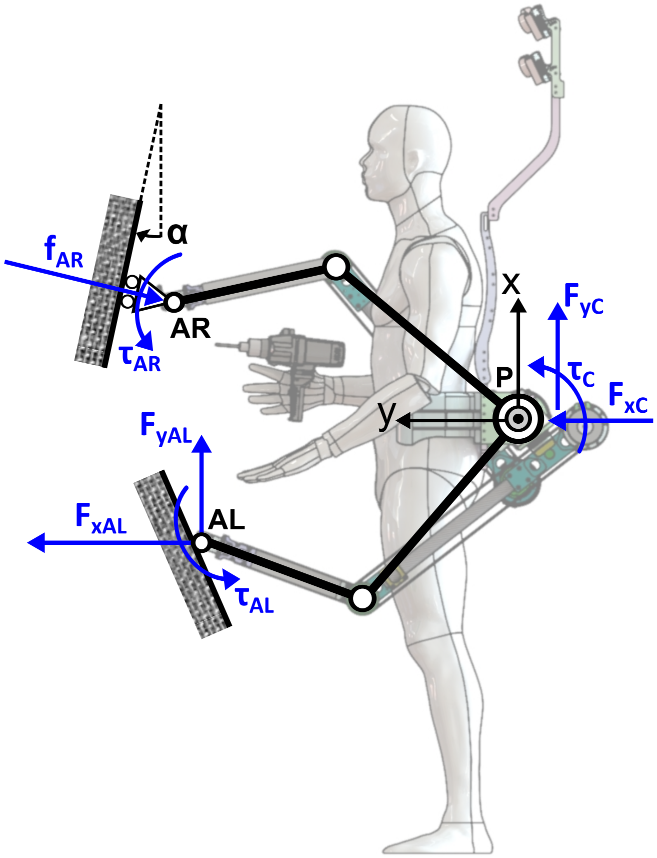

Fig. 2. Kinematic scheme of the SRL during the drilling task, applying the General Strategy. The robotic arms are drawn in black, while the ground reaction forces (f_{AR}, τ_{AR}, F_{xAL}, F_{yAL}, τ_{AL}) and the human hip forces (F_{xC}, F_{yC}, τ_C) are drawn in blue. $f_{AR} = \sqrt{F_{xAR}^2 + F_{yAR}^2}$ is the holding force of the drill jig. It is perpendicular to the contact surface, which has orientation α.

simply put in contact with the surface that needs to be drilled, on the desired location. Another advantage is the very fast and reliable engaging/disengaging process. The anchoring is realized by reaching the desired contact force, and is quickly released by moving the end effector away from the aircraft hull. No complicated end effector or grasping systems need to be used, making the holding system more reliable. In the following section, we will present three strategies to generate a perpendicular holding force and secure the drill jig during the drilling task.

III. DRILL JIG ANCHORING STRATEGIES

The main challenge presented by the drilling task is how to minimize the human effort while producing the required holding force at the drill jig. The base of the SRL is the human hip. This means that if the robotic configuration is unbalanced, the human must exert a restoring hip force in order to keep his/her position. The goal of the SRL is therefore that of generating a large drill jig contact force, while minimizing the required human workload. This can be achieved by using the free SRL arm (the one without the drill jig) to contact the environment in a convenient location. This SRL arm can then generate ground reaction forces aimed to secure the drill jig and relieve the human.

The structure of the problem is as follows (see Figure 2 and Table 1). The position of the SRL base (human hip) and the position and orientation of the drill jig are known. They are given parameter values determined by the task (hole that must be drilled) and by the current worker position. The goal of this analysis is to determine the best point where the free SRL arm must make contact with the environment. We also want to find the SRL joint torques that will originate the required drill jig anchoring force, while minimizing the human workload. Table I summarizes the parameters and unknowns of the problem (refer also to Figure 2).

A. Basic Strategy

The simplest drill jig anchoring strategy consists of generating with the free SRL arm a force which is equal and opposite to the holding force required at the bushing (Figure 3). In order to maintain static balance, the system needs a compensation torque τ_C.

$$\tau_C = f_{AR} \cdot d \tag{1}$$

This torque can be provided by the SRL wrists (they are in contact with the environment and can therefore shape the ground reaction torques). If τ_C surpasses the limits of the robot wrists, the exceeding part must be generated by the human hip.

The compensation torque τ_C depends on the magnitude of the holding force f_{AR} – which is a fixed parameter of the problem – and on the distance d between the holding force axis and the parallel axis passing through the other contact point (Figure 3). In order to reduce τ_C, this strategy requires reducing d. It is very convenient when it is possible to place f_{AR} and f_{AL} on the same axis. In most cases, however, reducing d entails decreasing the distance between the two robotic end effectors. This would place both robotic hands in the drilling area, creating unwanted obstacles to the movements of the worker. It is therefore necessary to develop an anchoring strategy that allows the SRL to generate the drill jig holding force without invading the drilling area.

B. Leaning Strategy

For a human, generating a strong continuous hip torque is uncomfortable and causes fatigue. In fact, this requires the constant contraction of the hip muscles. Conversely, for a standing human is simple and effortless to generate a static linear force in the horizontal plane. This can be achieved by leaning in the direction where the force must be created. Using the Linear Inverted Pendulum Model [10], this leaning force can be expressed as $F_y = mgy/L_H$, where L_H is the

TABLE I
VARIABLES OF THE PROBLEM

variables	type
f_{AR}, α, a_R, b_R	fixed parameters
F_{xC}, F_{yC}, τ_C, F_{xAL}, F_{yAL}, τ_{AL}, τ_{AR}, a_L, b_L	unknowns

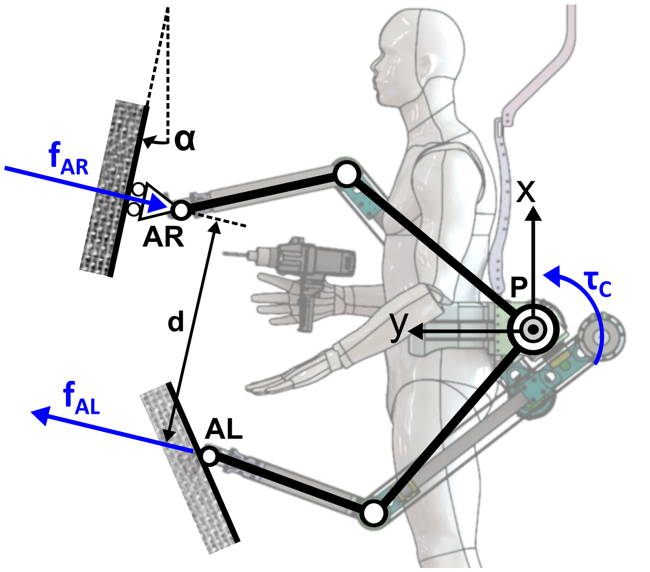

Fig. 3. Kinematic scheme of the SRL during the drilling task, applying the Basic Strategy. $f_{AS} = \sqrt{F_{xAL}^2 + F_{yAL}^2}$ is the holding force of the SRL arm without drill jig. Its direction is parallel to that of f_{AR}, its norm is the same, and its sense is opposite.

height of the human center of mass (COM), and deltay is the displacement from the equilibrium position in the y direction.

It is therefore possible to develop a drill jig anchoring strategy that constrains the human compensating force to be exclusively linear. The considered situation is shown in Figure 4: in order to generate the holding force f_{AR}, we want to use a robot contact force f_{AL} and a human hip force f_C in the same direction. These unknown forces can be determined writing the static equilibrium equations of the system:

$$\begin{cases} -f_{AL} + f_C - f_{AR} = 0 \\ f_C \cdot (d - d_R) - f_{AR} \cdot d = 0 \\ f_{AL} \cdot d - f_C \cdot d_R = 0 \end{cases} \tag{2}$$

Solving the system leads to the following solutions for the robot free contact force f_{AL} and for the human-generated force f_C:

$$\begin{cases} f_C = f_{AR} \frac{d}{d - d_R} \\ f_{AL} = f_{AR} \frac{d_R}{d - d_R} \end{cases} \tag{3}$$

Since d_R is fixed (it depends on the given drilling and human locations), the hip force f_C provided by the user can be reduced by increasing as much as possible the distance d between the two robotic end effectors. This is an advantage of the current strategy, because it means that the free robotic arm does not obstacle the movements of the worker in the vicinity of the drilling location. However, the limit of this strategy is that the required human force f_C is still large. In other words, the human effort is comparable (for admissible values of d and d_R) to the anchoring effect that we want to achieve. Moreover, the human can generate only the y component of f_C by effortlessly leaning forward. There is thus the need for a general drill jig anchoring strategy, able to identify the general ground reaction forces and torques that realize the desired holding force while minimizing human workload.

C. General Strategy

In the most general case, the SRL can generate 4 independent ground reaction forces in order to secure the drill jig. These free variables are F_{xAL}, F_{yAL}, τ_{AL}, τ_{AR} (see Figure 2). The human hip forces and torque F_{xC}, F_{yC}, τ_C are also unknown, and must be minimized. The location of the drill jig (a_R, b_R) is a problem input. The static equilibrium equations in this general case are:

$$\begin{cases} -f_{AR}\sin(\alpha) + F_{xC} + F_{xAL} = 0 \\ f_{AR}\cos(\alpha) + F_{yC} + F_{yAL} = 0 \\ -F_{yC}\ a_L + F_{xC}\ b_L + f_{AR}\ \cos\alpha\ (a_R - a_L) + \\ +f_{AR}\ \sin(\alpha)\ (b_R - b_L) + \tau_C + \tau_{AR} + \tau_{AL} = 0 \end{cases} \tag{4}$$

If we assume that the location of the other end effector (a_L, b_L) is known, the system is linear and can be written in matrix form as $Ax = b$, where

$$A = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ b_L & -a_L & 1 & 0 & 0 & 1 & 1 \end{bmatrix} \tag{5}$$

$$x = [F_{xC}\ ,\ F_{yC}\ ,\ \tau_C\ ,\ F_{xAL}\ ,\ F_{yAL}\ ,\ \tau_{AL}\ ,\ \tau_{AR}]^T \tag{6}$$

$$b = \begin{bmatrix} f_{AR}\ \sin(\alpha) \\ -f_{AR}\ \cos(\alpha) \\ -f_{AR}\cos(\alpha)(a_R - a_L) - f_{AL}\sin(\alpha)(b_R - b_L) \end{bmatrix} \tag{7}$$

Since matrix A has full row rank and $m = 3 < n = 7$, the system has infinite solutions. The solutions x represent the ground reaction forces and human forces that generate

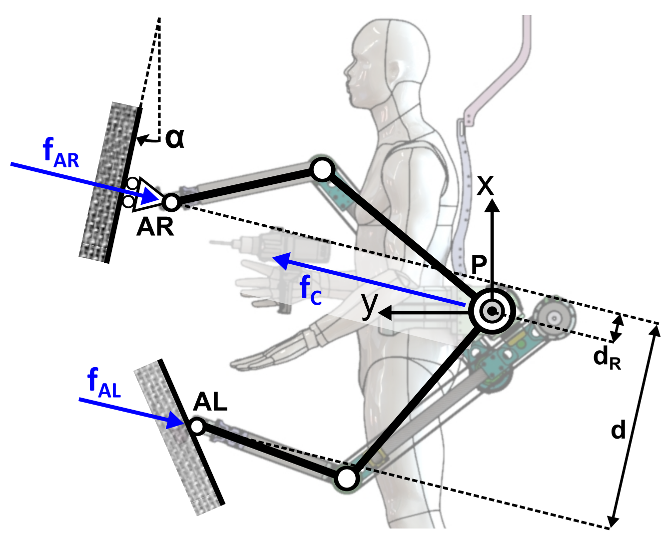

Fig. 4. Kinematic scheme of the SRL during the drilling task, applying the Leaning Strategy. $f_C = \sqrt{F_{xC}^2 + F_{yC}^2}$ is the norm of the human hip force. f_{AR}, f_{AL} and f_C are parallel.

the desired holding force f_{AR}, while maintaining the system in static equilibrium. Section IV will present an optimization technique to select the most convenient solution, and use its results to identify the best robot configuration.

It is important to point out that the results of this section hold in general for any wearable robot that has two contact points with the environment. These results do not depend on the specific number of links or joint types of the wearable robot. The kinematic structure of the robot will come into play when determining the necessary joint torques (Section V).

IV. OPTIMIZATION

The system found applying the general drill jig anchoring strategy has infinite solutions. The optimal solution is the one which minimizes the user workload required to anchor the drill jig. The human workload is determined by the forces and torque that the hip must exert in order to keep the system in static balance: F_{xC}, F_{yC}, τ_C. In this analysis, we include all of these values in a single scalar measure of human workload: the compensation energy E_C. This quantity is the equivalent energy that the human hip would have to provide if it was a passive element composed by three springs (two linear and one rotational). The definition of E_C is as follows

$$E_C = k_x(\Delta x)^2 + k_y(\Delta y)^2 + k_\theta(\Delta\theta)^2 \qquad (8)$$

Since the equivalent displacements Δx, Δy, $\Delta\theta$ are linearly related to the hip forces and torque ($F_i = k_i\ x_i$), the expression of the compensation energy can be re-written as

$$E_C = \frac{F_{xC}^2}{k_x} + \frac{F_{yC}^2}{k_y} + \frac{\tau_C^2}{k_\theta} \qquad (9)$$

The values of the three hip spring constants can be adapted from the biomechanical literature [11]. When a human is standing, the body behaves like an inverted pendulum and the equivalent stiffness at the hip is largely determined by the ankle stiffness (anterior/posterior direction: $k_{frontal} = 800$ Nm/rad). The equivalent hip stiffness can be determined assuming small displacements (leg length $L_H = 1$ m): $k_y = k_{frontal}/L_H^2$. Stiffness in the x direction is higher ($k_x = 1600$ N/m), because the users legs are parallel to the x axis (Figure 2). Conversely, hip rotational stiffness is lower ($k_\theta = 400$ N/m), because hip muscles are weaker than the leg ones. Hip stiffness parameters (k_x,k_y,k_θ) allow to determine E_C given the values of F_{xC}, F_{yC}, τ_C.

Since the goal of the optimization is to find the solution x which minimizes E_C, we select a weight matrix W that attributes a cost to the elements of x (see eq. 6). The cost of every element is based on its weight in the expression of E_C:

$$W = diag\left(\frac{1}{k_x}, \frac{1}{k_y}, \frac{1}{k_\theta}, w_{min}, w_{min}, w_{min}, w_{min}\right) \qquad (10)$$

where $w_{min} = min(1/k_x, 1/k_y, 1/k_\theta) \cdot 0.1$. Note that the only elements with relevant weights are the ones that determine E_C. The other elements have negligible weights (compatibly with the fact that W must be positive-definite).

The optimization problem can be solved with the Lagrange Multipliers [12]. We define the following Lagrangian function:

$$L = x^T W x + \lambda^T(b - Ax) \qquad (11)$$

where the first term is the cost function (based on W), and the second term is the system of constraints (based on the general strategy derived in the previous section). The solution x which minimizes the cost while respecting the constraints is

$$\begin{cases} \partial L/\partial\lambda = 0 \\ \partial L/\partial x = 0 \end{cases} \qquad (12)$$

$$\Rightarrow\ x_{opt} = W^{-1}A^T\left(AW^{-1}A^T\right)^{-1} b \qquad (13)$$

This solution contains the ground reaction forces and human hip forces that anchor the drill jig to the ground, while minimizing the human workload. The linear system on which the solution is based (equations 4-6) was derived assuming that the contact point of the free SRL arm (a_L, b_L) was fixed. It is therefore possible to repeat the same optimization for every contact point within the workspace of the SRL. The results (optimal E_C that can be achieved given a particular contact point) are visualized in Figure 5.

In a manufacturing environment, though, the number of available contact points is limited. The free robotic arm can only make contact with the environment in the intersection between the aircraft structure surface and its workspace. Such a situation is represented in Figure 6. When limited contact points are available, the ground reaction forces (and associated optimal E_C) are calculated only for those points. The best overall ground contact is then the one that yields the smallest optimal E_C (see Figure E_C).

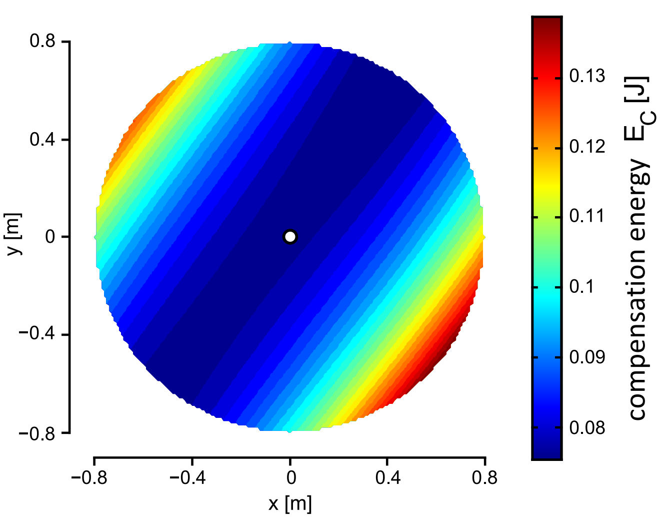

Fig. 5. Optimal E_C for every contact point within the robot workspace. The white point represents the robot base (point P in Figure 2).

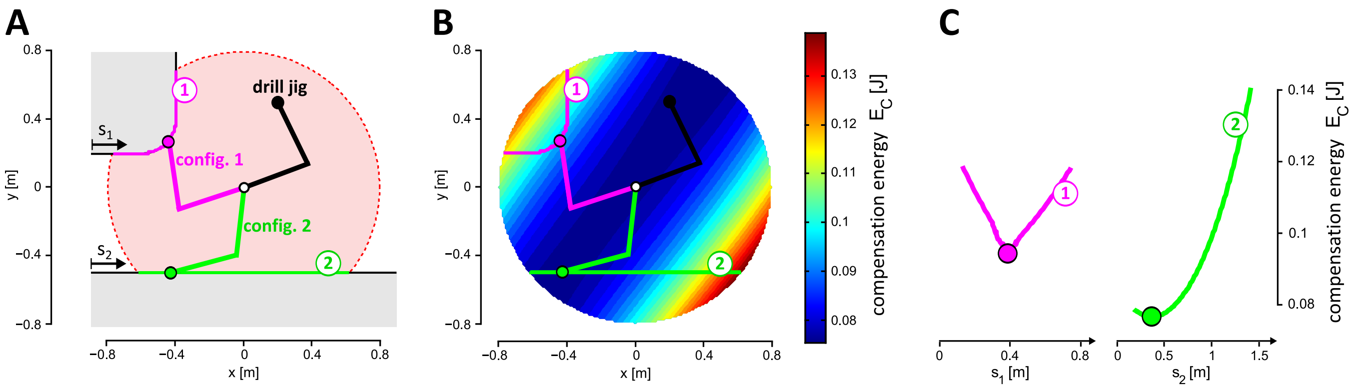

Fig. 6. The black lines represent the SRL arm which is holding the drill bit. The green and magenta lines represent the optimal configurations of the other SRL arm. A) Intersection between the SRL workspace (red) and an arbitrary environment profile (grey). B) Plot of the available contact points (green curve (1) and magenta curve (2)) over the E_C map determined before (see Figure 5). C) Visualization of the value of E_C for the available contact points (curves (1) and (2) in the workspace). E_C is plotted along coordinates s_1 and s_2 (the position of the contact points along the environment profile). The optimal contact points, outlined with dot markers, are the ones that minimize E_C. The magenta and green SRL configurations in A) and B) correspond to these two minima.

The general anchoring strategy, combined with the optimization method described above, is able to select the most convenient SRL configuration because it does not pose any constraints on the ground reaction forces (unlike the basic strategy and the leaning strategy). Figure 7 and Table II visualize two optimal SRL configurations, with their associated ground reaction forces and hip forces. It is evident that the anchoring force is generated by the robot with negligible human effort (small F_{xC}, F_{yC} and τ_C).

Table II reports the ground reaction forces and hip forces in the two optimal cases (see also Figure 7). It also shows the coordinates of the optimal ground contact points.

V. DISCUSSION

The optimization process described in the previous section determined the SRL configuration and external forces that anchor the drill jig to the aircraft while minimizing human workload. We now find the robot joint torques that must be applied in order to realize the optimal static equilibrium. The values of the ground reaction forces and torque are known for both robotic arms. These values are either contained in the vector x_{opt} or can be determined from the problem parameters ($F_{xAR} = -f_{AR}\sin(\alpha)$, $F_{yAR} = f_{AR}\cos(\alpha)$). Knowing the ground reaction forces (equal and opposite to the end effector forces) allows us to write the following expressions for the joint torques

TABLE II
OPTIMAL SRL CONFIGURATIONS

quantities	config. 1	config. 2
$(a_L,\ b_L)$ [m]	(-0.44, 0.27)	(-0.43, -0.50)
F_{xC} [N]	7.6	6.7
F_{yC} [N]	6.8	6.3
τ_C [Nm]	0.8	0.1
F_{xAL} [N]	67.4	68.3
F_{yAL} [N]	123.1	123.6
τ_{AL} [Nm]	30.0	3.7
τ_{AR} [Nm]	30.0	3.7

$$\begin{bmatrix}\tau_{1L}\\ \tau_{2L}\\ \tau_{3L}\end{bmatrix} = -J_L^T \begin{bmatrix}F_{xAL}\\ F_{yAL}\\ \tau_{AL}\end{bmatrix} \tag{14}$$

The same expression is applied also to the other robotic arm (with subscript R). J_L and J_R are the Jacobian matrices of the two SRL arms in the kinematic configuration that corresponds to x_{opt}.

Up to this point, we did not make any assumption on the particular structure of the wearable robot. These results hold for any wearable robot with two end effectors (the drill jig and a gripper). In the case of the SRL prototype (Figures 1 and 2), the robotic arms have 3 degrees of freedom in plane xy.

The solution for the joint torques τ_L and τ_R is unique. The SRL joint torques for the two considered configurations (magenta (1) and green (2), see Figures 6 and 7) are reported in Table III. If the robotic arms had a different number or type of actuators, the Jacobian matrix would change accordingly.

The optimization method presented in this study does not take explicitly in account the limitations to the joint torques, or to the electromagnets gripping force. If the maximum values of these quantities are surpassed, the drill jig holding force must be decreased until all constraints are met.

The results shown in Section IV confirm that the General Strategy is superior to the Basic and Leaning Strategies. The general method always minimizes the human workload, for any environment profile. The examples reported in Table II and III show that the human workload is one order of magnitude less than the holding force exerted on the drill jig. Conversely, the other two methods are effective only in particular situations (gripper close to the drill jig for the basic strategy, and gripper far from the drill jig for the leaning strategy) and require high human workloads in the other cases. The basic and leaning strategies can be viewed as particular cases of the general strategy, which the optimization algorithm will select if their particular conditions are met. This is evident in the case of configuration 2 (Figure

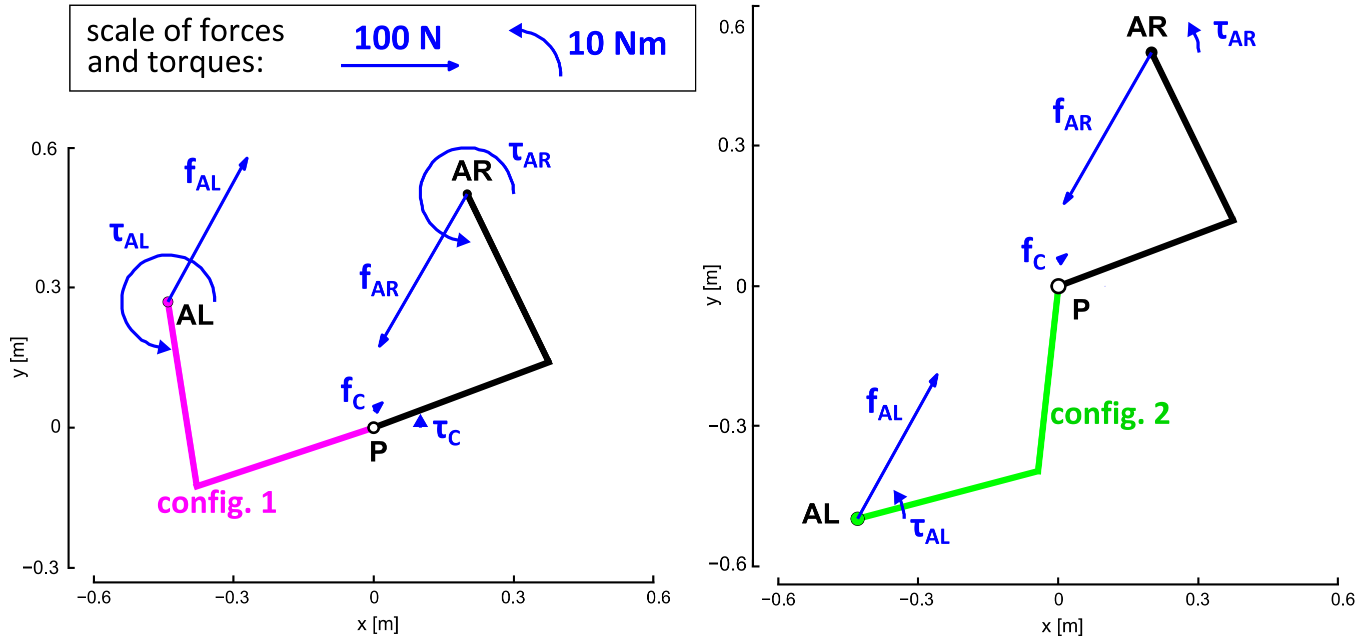

Fig. 7. Visualization of the ground reaction forces and human hip forces in the two optimal configurations identified in Section IV (see also FIgure 6). The points and forces are defined in Figure 2. The length of the vectors is proportional to the magnitude of the forces and torques (see box for scale). Configuration 2 achieves the minimum possible E_C given the available points. It also requires smaller joint torques on the SRL joints (wrist torques plotted; for the other joints, see Table III).

7), where the optimization algorithm almost cancels out τ_C by positioning the contact point AL along the direction of f_{AR}, and requiring a ground reaction force f_{AL} which is similar in magnitude but opposite in sense (compare with section III.A).

The optimization method can also be adapted to compensate for the weight of the SRL. In this case, it suffices to modify system $Ax = b$ by imposing the value of $F_{xC} = -mg$ (F_{xC} becomes a fixed parameter). This way, the optimization algorithm will find the SRL configuration and joint torques that anchor the drill jig, compensate for the weight of the machine, and minimize the user workload.

VI. CONCLUSIONS

The Supernumerary Robotic Limbs (SRL) are two wearable robotic arms that augment the skills of their human user, enabling the execution of complex or fatiguing tasks that would normally require the collaboration of two or more workers. The SRL has been designed to address the needs of the aircraft manufacturing industry, where productivity is limited by difficult tasks and an aging workforce. Our vision for the SRL is to become a functional extension to the human workers, conjugating robotic accuracy and strength with human intelligence and adaptability.

TABLE III

OPTIMAL SRL JOINT TORQUES

joint torques [Nm]	config. 1	config. 2
τ_{1L}	42.3	15.3
τ_{2L}	4.0	37.1
τ_{3L}	-30.0	-3.7
τ_{1R}	-41.6	-15.2
τ_{2R}	-79.7	-53.4
τ_{3R}	-30.0	-3.7

In this paper, we focused on a drilling task where the goal of the SRL is ensuring that the hole respects positional and orientation tolerances despite the presence of disturbance forces. This is achieved by using a drill jig equipped with a central hole (bushing). Once the robot has positioned and anchored the drill jig on the aircraft surface, the worker uses the bushing to guide the drill bit. The anchoring effect is achieved by pressing the drill jig on the surface of the aircraft structure.

The results presented in Section IV and V show that the SRL is effective in aiding the user during the considered drilling task. Our algorithm is able to select the optimal robot configuration given a limited number of available contact points with the environment. The algorithm can identify the ground reaction forces that secure the drill jig to the aircraft structure, while minimizing the human workload. It also computes the joint torques necessary to create the desired static equilibrium.

This paper demonstrated a novel application for wearable robotic arms that are kinematically independent from the user. The SRL is free to select the configuration and joint torques that are most effective in assisting the user during a drilling task.

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