Multipurpose Supernumerary Robotic Limbs for Industrial and Domestic Applications*

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***Abstract*—Robotic exoskeleton arms have been around for a long time and they have successfully evolved from research prototypes to commercial products. Multipurpose supernumerary robotic limbs (MSRLs) have been recently introduced as new types of aids which do not directly replace missing limbs, but they are additional mechanical arms with changeable end-effectors which can be worn by the user to provide needed functionalities. This paper presents the mechanical design and kinematics modelling and control of a MSRL system. The MSRL presented could have good application in industrial and domestic situations.**

Keywords—robotic arm; wearable personal robotics; leader-follower method; AHRS; kinematics; mechanical design

I. Introduction

Assembly lines in manufacturing industries are usually semi-automated, and workers are still required to perform repetitive and strenuous tasks at rapid rates. Multipurpose supernumerary robotic limbs (MSRLs) have been recently developed as new types of assistant robots which do not directly replace missing limbs or enhance existing limbs, but they are additional mechanical arms with changeable end-effectors that can be worn to provide needed functionalities. If workers were to wear these new MSRLs during production, the mechanical arms would be able to perform simple and repetitive tasks, while the natural arms of the human can perform operations which require high dexterity—thus reducing the overall amount of time taken by the worker to process each job. The MSRLs can be used for operations where more than two natural arms are required, but hiring an additional worker is not feasible [1-4]. For example, a worker in an assembly line might be required to lift and hold a fixture in place, and drill a hole in it using a drilling machine. Using the MSRLs, the user can lift and place the fixture at the right place with his/her natural arms, while the mechanical arms can be programmed to drill the hole at the required point [1].

In the home environment, the MSRLs can aid in performing domestic tasks requiring more than two natural arms. For example, when washing up, a user wearing an MSRL system can hold the dish in place with his/her natural arms, while the robotic arms can be programmed to apply washing-up liquid and scrub it. If an open source platform is selected, any developer will be able to develop their own sub-systems such as end-effectors which can store, say, liquid soap in a built-in refillable chamber. The liquid soap could be connected to the scrubber via a self-dispensing tube to effectively wash the dishes. In this way, simple repetitive tasks can be automated via a sophisticated human-robot collaborative solution, and the productivity of the human can be increased. Further simplifications to enhance the final design and manufacture using 3D printing and using simple DC servo motors can reduce the cost of the whole system.

The overall challenges to study human/MSRL collaborative systems to achieve required performances are studied in this paper and initial results are presented. The initial requirements considered here are to focus on precision of movement, reduction of the overall weight and make the final MSRL design as compact and portable as possible.

II. Related Work

Davenport and Parietti from Massachusetts Institute of Technology, worked on supernumerary robotic limbs (SRLs) under Prof. Harry Asada. The SRLs, consisting of multiple degrees of freedom, were specially designed for the aerospace industry under a project sponsored by Boeing [1-4]. MSRL systems are inspired by the original SRL concept, but the approach and design of the arms are fundamentally different. The SRL systems are designed for handling heavy payloads commonly found in aerospace components, and hence make use of series elastic actuators to provide the robotic arms with the high torques needed [1-3]. The robot loads mainly the wearer's legs, without burdening the arms or the back and the specifications of the robotic limbs have been inspired by the properties of human arms in terms of torques, weights and joints' series elasticities [3]. Also, the algorithm used for state trajectory estimations of the mechanical arms in the SRL uses traditional Kalman Filters [3]. MSRLs on the other hand, are designed for portability and compactness, so they can be used in industrial and domestic environments where the payloads smaller. The actuators used in MSRLs are inexpensive Rhino DC servomotors with torque of 120 kg-cm while running at 10 RPM. Sensor data fusion/state estimation of the trajectories of the MSRL's mechanical arms can be performed via the Attitude and Heading Reference System (AHRS) developed by Madgwick [5]. This consists of simpler and fewer mathematical operations than those needed in Kalman filtering, and hence puts lower load on the embedded microcontrollers. This enables us to use smaller and inexpensive microcontrollers, making MSRLs more compact and portable than SRLs [6].

Figure 1: MIT d'Arbeloff Laboratory

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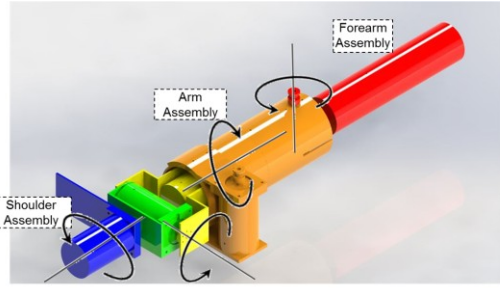

Figure 2: SolidWorks Schematic Model

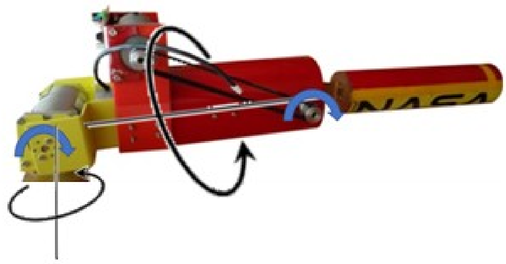

Figure 3: Realization of 3D Model

III. Design of MSRLs

As stated, MSRLs are designed for compactness and portability; this is achieved by placing all the motors close to each other, and siting the arrangement at the shoulder mechanism. This way, the torque available at the end-effectors is maximized, because the moments caused by the weight of the motors and motor attachments are reduced. All the four joints in the robot arm are revolute, and are driven by rotary actuators. One entire arm weighs under 3 kg, and occupies a volume of 600mm x 300mm x 170mm (L x B x H). Figure 2 shows a 3D schematic model of one MSRL arm, and Figure 3 shows the realization of the prototype. It consists of five links, represented by five different colours in Figure 2, which are connected by four joints. Identical to natural human arms, the MSRL consists of three DOFs at the shoulder joint and one DOF at the elbow joint. This allows the MSRL to be able to perform most simple tasks that can be performed by human arms (up to the wrist).

A. Kinematics model

TABLE I. D-H Parameters of SRL

i^{th} joint	α_{i-1}	a_{i-1}	d_i	θ_i [1]
1	0	0	0	a
2	$\pi/2$	0	0	b
3	$-\pi/2$	0	0	c
4	$\pi/2$	0	d_4	d
tool	$-\pi/2$	a_{tool}	0	0

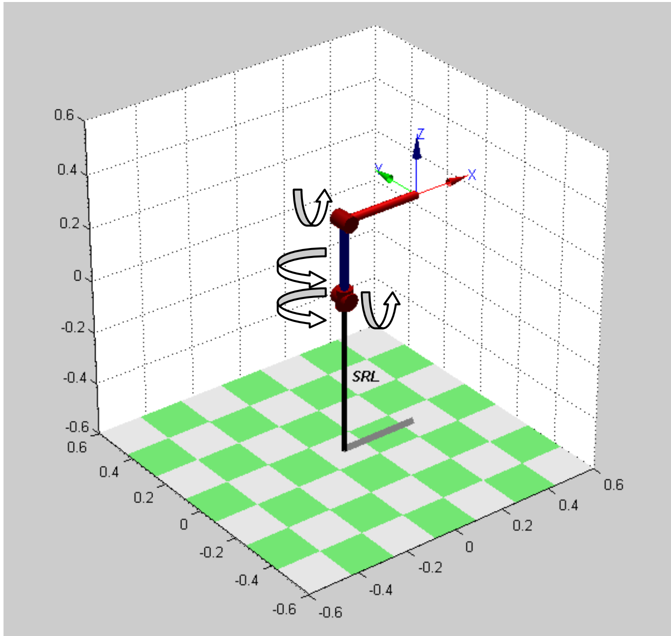

Figure 5: MATLAB Robotics Toolbox Simulation

The Denavit-Hartenberg (D-H) parameters of the MSRL have been derived and are shown in Table I. Using these D-H parameters, we were able to model the MSRL using the MATLAB Robotics Toolbox, and run simple forward kinematics simulations (Figure 5). We were also able to compute the inverse kinematics through numerical methods, using the *ikine()* function [13].

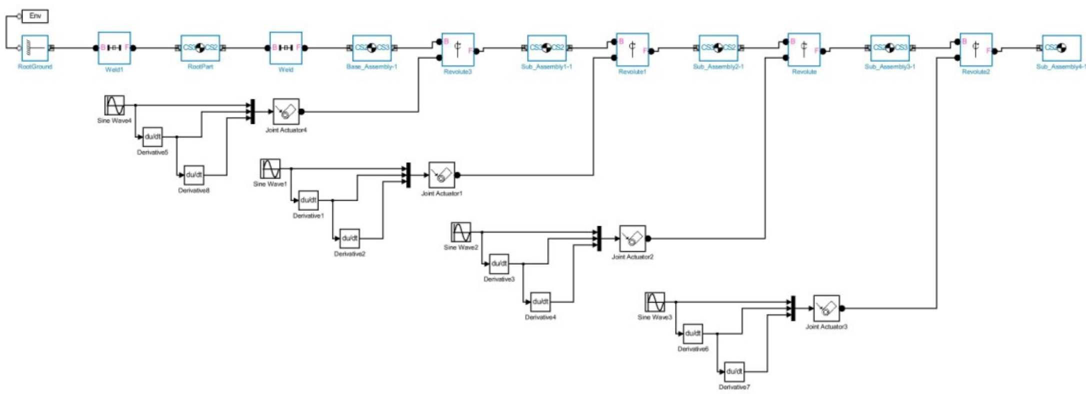

Figure 4: Simulation of simple harmonic motion for each motor joint

[1] θ_i represents the joint variables (a, b, c and d are the four joint variables)

B. Simulation and implementation

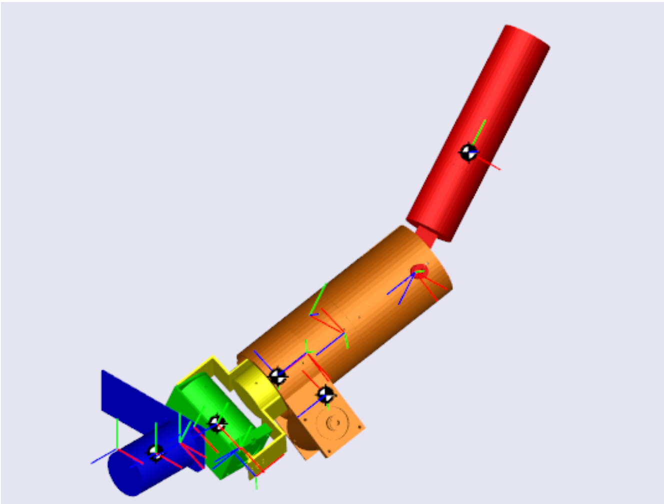

Figure 6: MSRL during simulation

Figure 7: Implementation

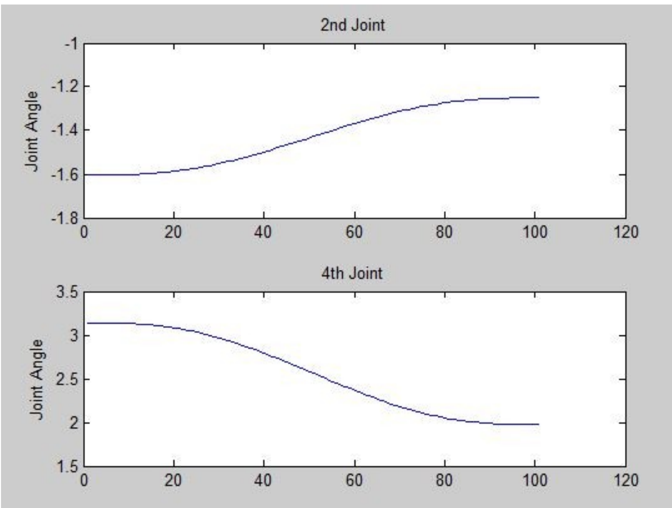

Figure 8: Joint trajectory for straight line motion in global x-axis

Figure 4 shows the Simulink control block diagram consisting of five sub-assembly blocks connected by four revolute pair blocks. The revolute pairs are given joint-actuator blocks, which have three parameters each: position, velocity and acceleration. For performing the basic simulation, we have given a sine wave as the position signal, which is differentiated by the derivative block to obtain velocity, and this in turn is differentiated by another derivative block to obtain acceleration. This results in a simple harmonic motion in all the joint actuators. Figure 6 shows the robot during simulation, along with the body attached coordinate frames and the centre of masses. Figure 7 shows the robot performing a simple "Hi" gesture. Currently, the robot is connected to a fixed stand, in order to verify the feasibility of the overall design, by reducing the errors caused due to mobility via the human wearer. Figure 8 shows the joint trajectories of the robot while moving in a straight line from x=0.3 to x=0.5 in the global coordinate frame.

C. Robot control methods

We propose two methods for controlling the MSRL system; the first approach uses the Leader-Follower method (Figure 9) and the second is by using a Graphical User Interface (Figure 10). Method 1 is useful when the human arm motions are to be recorded by the controller, and the MSRL system has to repeat the same motion over and over again [1]. The second (GUI) method is helpful when the robot is to be programmed to move by precise angles and/or distances.

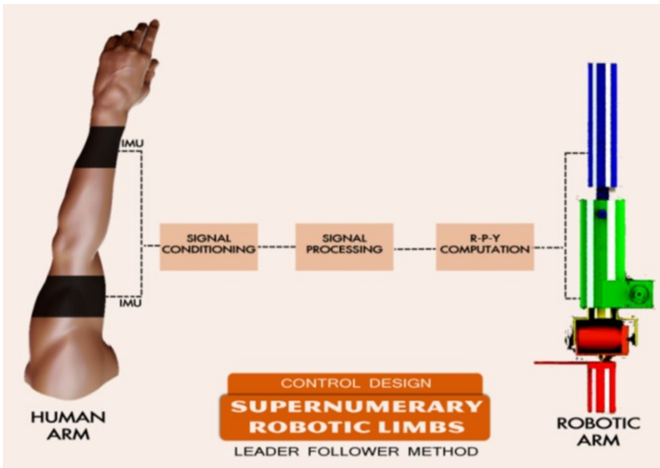

Figure 9: Method 1: Leader-Follower method for controlling the MSRL

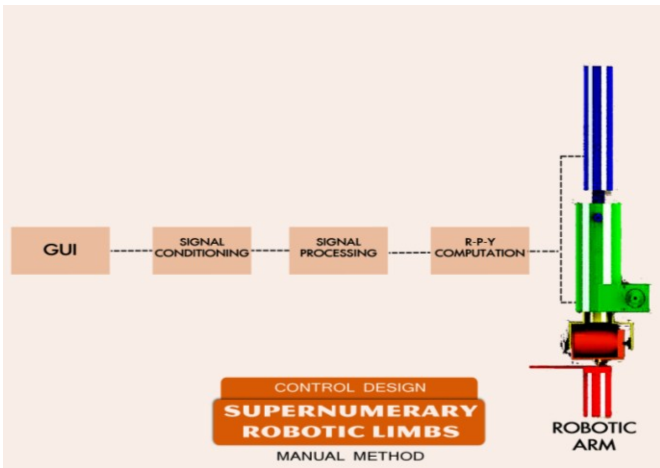

Figure 10: Method 2: GUI method for controlling the MSRL

The Leader-Follower method requires Inertial Measurement Unit (IMU) sensors to be fitted to the human elbow and to the human wrist. The movement of the human arms can be tracked by obtaining the IMU measurements and performing simple trigonometric calculations. The raw values obtained by the IMUs cannot be used directly, because of the error caused due to yaw-drift. The error must be compensated by using an appropriate magnetometer and a GY-86 IMU sensor module has been used here, which contains a 3-axis accelerometer, a 3-axis gyroscope, a 3-axis magnetometer and a barometer. The algorithm used for error compensation is the Attitude and Heading Reference System (AHRS) mentioned previously; this is a novel orientation algorithm designed to support a computationally efficient, wearable inertial human motion tracking system. The algorithm uses a quaternion representation, allowing accelerometer and magnetometer data to be used in an analytically derived and optimized gradient descent algorithm to compute the direction of the gyroscope measurement error as a quaternion derivative [5, 10]. The quaternions q_0, q_1, q_2, and q_3 can be converted into Euler/Tait-Bryan angles ϕ, θ and ψ for easier operations, using the following equations:

$$\begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} = \begin{bmatrix} \mathrm{atan2}(2(q_0q_1 + q_2q_3), 1 - 2(q_1^2 + q_2^2)) \\ \arcsin(2(q_0q_2 - q_3q_1)) \\ \mathrm{atan2}(2(q_0q_3 + q_1q_2), 1 - 2(q_2^2 + q_3^2)) \end{bmatrix}$$

Figure 11: Quaternions to Euler/Tait-Bryn angles[2]

The FreeIMU library developed by Varesano provides ready-made code for obtaining the AHRS-filtered values of the IMU sensors [12].

Figure 12: State Estimation using FreeIMU Library with AHRS algorithm [12]

Figure 12 shows the yaw-pitch-roll angles of the sensor after the data are filtered using the AHRS algorithm; the AHRS filter is almost as accurate as the Kalman Filter. A direct comparison of the AHRS output with the Kalman filter output can be seen in the study carried out by Madgwick [10].

[2] http://wikipedia.org/wiki/Conversion_between_quaternions_and_Euler_angles

IV. Conclusions and Future Work

The paper has shown that it is possible to design and develop an additional pair of auxiliary mechanical arms that can aid in carrying out tasks which normally require more than two natural arms. The Leader-Follower method, using IMUs attached to the human arms, and running the AHRS algorithm has been shown to provide an efficient way to interact with MSRLs and to control such systems effectively. MATLAB and Simulink can be used to simulate and verify the accuracy of the Leader-Follower method. More optimization of motion planning in MSRLs will enable the robotic arms to perform advanced tasks with appreciable dexterity. With advances in 3D printing technology, we can expect MSRLs to be manufactured inexpensively, and in the near future, they may be put to use in wide range of domestic applications as well as in industrial manufacturing scenarios. The contribution of this paper is the mechanical design and the kinematics model of the MSRL with the use of the AHRS algorithm for estimating the state of the mechanical arms and for human motion tracking.

Future work includes deriving of inverse kinematics and dynamic equations and experimenting with different motion planning algorithms for leader-follower control. The GUI for controlling the MSRL through a computer or a mobile device wirelessly is also to be developed.

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