3DOM: A 3 Degree of Freedom Manipulandum to Investigate Redundant Motor Control

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Abstract—This paper presents a novel robotic interface to investigate the neuromechanical control of redundant planar arm movements. A unique aspect of this device is the third axis by which the wrist, and hence the pose of the arm can be fully constrained. The topology is based on a 5R, closed loop pantograph, with a decoupled wrist flexion/extension cable actuated mechanism. The design and characterization (in terms of range of motion, impedance, friction and dynamics) are described in this paper. This device is lightweight, safe and has high force capabilities and low impedance. Simple experiments illustrate the advantages of this device for the investigation of redundant motor control in humans.

Index Terms—Human motor control, haptic interface, parallel robot, redundant arm control

1 INTRODUCTION

In the last 30 years, robotic interfaces have enabled researchers to unfold important aspects of human motor control [1], [2], [3], [4]. More recently, the use of robotic interfaces to facilitate neuro-rehabilitation has been investigated [5], [6], [7], [8]. Robotic interfaces used to study the neuromechanics of the upper limb range from single degree of freedom (DOF) devices [9], [10] to full arm exoskeletons [11], [12]. In particular, many studies have investigated planar arm movements using a 2 DOF interface [13], [14], [15], [16], [17]. This enables investigating the control of multi-DOF kinematics, coupled and nonlinear dynamics [18] as well as the redundant musculature of the arm [19], while providing good visualization of trajectories and enabling analysis in a two dimensional space.

One of the most important issues in human motor control is to understand how the central nervous system distributes the movement to the redundant system of the body, as was formulated by Nikolai Bernstein a century ago [20]. However there have been very few tools to investigate this question systematically. The only systems that could be used to apply forces on all joints of the arm so far consist of exoskeletons which are very difficult to design and control in a ‘transparent’ way, i.e., without offering significant resistance to the movement. Furthermore, systems involving the whole arm provide six or seven DOF data which are difficult to interpret and visualize.

This motivated us to develop the 3DOM interface (for “three degree of freedom manipulandum”), which is a system able to study the control of the kinematically redundant arm moving in a plane (Fig. 1A). The paper demonstrates its advantageous dynamic properties and how it can be used to investigate the control of the redundant arm. While 3DOM is not conceived to carry out robot-assisted neurorehabilitation, it is used every day at the Neurological Hospital for Neurology and Neurosurgery at Queen Square in London, in order to investigate sensorimotor control in stroke survivors as well as in healthy subjects.

Our goal was to develop a safe robotic interface to investigate kinematically redundant planar arm movements. This redundancy is due to the arm having more DOF than is required to carry out a task, and it is unclear how the central nervous system shares the movement between the shoulder, elbow and wrist joints. The redundancy of planar movements is illustrated by the difference between taking a glass or a cup. In the latter case the hand must be oriented properly in order to take the cup successfully, while a glass can be grasped in any orientation. To simplify experiments and motion analysis, we decided to focus on horizontal planar arm movements in which the hand pose can be described by the Cartesian coordinates and orientation (using $x_1, x_2, \theta$, see Fig. 1A). This paper describes this interface, its design and properties, and illustrates its capabilities for investigating the control of redundant arm movements in three simple experiments carried out by one subject.

2 SPECIFICATIONS

Neuromechanical investigations require a device offering minimal resistance to motion (i.e., low impedance), high rigidity to transmit fast force changes, isotropic friction/force and force capability inside the workspace [14]. This further requires powerful actuators to generate high force levels at the end-effector, as well as smooth control to accommodate the high temporal and spatial resolutions of tactile perception and proprioception. Many previous interfaces have fulfilled these requirements by using a semi-parallel design [13], [16], [17] or a fully parallel design [14], [21]. In both cases, a closed mechanical chain allows the motors to be placed at the shoulders, resulting in reduced limb weight and enabling highly dynamic movements. This is in contrast to robots based on a serial design,
which have to carry the weight of their actuators during movement and thus have greater inertia (e.g., [22]). In both parallel and serial based robots, low end point inertia is crucial to transmit forces at higher speeds. Additionally, when robots are designed for human interaction, strict safety measures must be implemented both in hardware and software in order to minimize the risk of causing harm. The importance of these safety measures increases with robot force capabilities and workspace. Such measures must prevent the robot from colliding with the human, overextending any limb beyond its natural range of motion or applying excessive forces that might cause bodily injury.

When transmitting forces from a robot to a human wrist, the subject’s fingers and palm should be rigidly attached to the support in order to prevent any undesirable movement from occurring and allow recording the interaction forces between the hand and the robot with fine detail. Furthermore, wrist modules should be ergonomic and allow fitting hands of different sizes and good alignment of the mechanical and anatomical centers of rotation.

3DOM, the novel robotic interface presented in this paper, is based on a five-bar (5R) parallel mechanism controlling an end-effector handle in the $x_1x_2$ plane with a decoupled cable driven transmission mechanism, which can control arm and wrist flexion/extension (Fig. 1). The topology of 3DOM enables the application of local joint torque fields through the device’s endpoint control, eliminating the need for an exoskeleton and mechanical adaptation to accommodate differing limb lengths of users. For example, elbow damping can be applied via the wrist end-effector.

3D OM Interface and Modeling

3.1 Mechanical Design: Topology and Geometry

The parallel mechanism of the 5R topology (similar to a person holding the hands together with the motors at the shoulders, Fig. 2A) was selected to provide a stiff but relatively light mechanism. The design goal was to achieve $>50$N force at the wrist endpoint over a rectangular workspace of $50 \times 30$ cm with $<1$ mm spatial resolution at the workspace center. The wrist axis was required to produce a peak torque of 4 Nm over a 180 degree range. These parameters were determined via several preliminary experiments to approximate the typical range of motion and force/torque characteristics of the human arm acting about the
shoulder. The workspace and force levels presented by 3DOM in xy are similar to those of Braccio di Ferro [16], vBot [17] and Manus [23].

For conventional 2DOF operation, the wrist axis of the device is equipped with a vertical handle (Fig. 1C). For 3DOF operation, a support was designed so that large and small hands could be fixed rigidly, but without discomfort (Fig. 1B). This dedicated handle yields excellent transfer of motor torque to the wrist flexion/extension. Equipped with this support and appropriate torso restraint the manipulandum can accurately measure and constrain posture of the arm in the three degree-of-freedom horizontal movements.

The wrist handle frame was milled out of an L-shape HE30TF Aluminum section (101 × 51 × 6 mm³) with a weight of 137 g. The plastic shell was vacuum formed from a 2 mm acrylic sheet upon a hand sculpted buck. Stainless steel standoffs connect the shell to the frame. Velcro straps rigidly lock each finger individually as well as the thumb, the dorsal side of the palm and the wrist (Figs. 1D and 1E). A detachable support allows constraining the subject’s forearm (Fig. 1A). This support rotates freely (independently from the wrist) with respect to the wrist rotation axis.

### 3.2 Kinematics Analysis

The kinematic relations are derived using closure constraints. With the variables described in Fig. 2A, the robot wrist (P₃) and elbow (P₂ and P₃) position can be calculated as:

\[
P₃ = P₉ + \frac{L₉^2 - ||v||^2/4}{||v||} \begin{bmatrix} v_2 \\ -v_1 \end{bmatrix}, \quad v \equiv P₁ - P₂,
\]

\[
P₂ = P₁ - Lₐ \begin{bmatrix} \cos q₁ \\ \sin q₁ \end{bmatrix}, \quad P₃ = P₂ - Lₐ \begin{bmatrix} \cos q₂ \\ \sin q₂ \end{bmatrix}.
\]

Using these relations, the differential kinematics can be determined analytically or numerically using the Jacobian \( J(q) = \left[ \partial x / \partial q \right] \). Fig. 2B shows the condition number over the robot’s workspace. This number is defined as \( k(J) = k(J^{-1}) = ||J^{-1}|| ||J|| \) and is a good measure of the mechanism’s singular positions, thus its accuracy and dexterity [24]. Minimum condition = 1 corresponds to the desirable situation where the robot is capable of generating the same level of endpoint force or velocity in all directions for a given magnitude of motor torque. With the selected 30 cm distance between motor spindles, \( Lₐ = 26.25 \) cm and \( L_f = 45 \) cm, the mechanism has good isotropy: \( k < 5, k < 3 \) in 97 percent of the workspace, and \( k < 2 \) in 84 percent of it.

### 3.3 Dynamic Model and Compensation

Identification of friction and inertia of the 3DOM was achieved by using a simplified model of the device’s dynamics, which neglects the rotational inertia of the coupling between the distal links (Fig. 2A). Nevertheless, the model does take into account the masses of all the links as well as the handle, although the mass of the left and right distal links \( m_{l23} \) for mass of the link \( P₂ P₃ \) and \( m_{r23} \) for \( P₃ P₄ \) were each distributed equally to the wrist \( P₃ \) and upper arm elbow points \( P₂ \) and \( P₄ \). Additionally, the mass of the handle \( m_{h6} \) was considered to be a point mass at \( P₃ \). Furthermore, friction was considered to act only at the shoulder joints, about the motor spindles.

This simplified model was selected to minimize computation. The relative low mass of the carbon fiber links (compared to the aluminum and steel components of the joints), as well as low rotational accelerations of the distal links (compared to the shorter proximal links) obtained during simulations of the system’s CAD model, result in a negligible contribution of the rotational inertia of the distal carbon fiber links to the system’s dynamics.

With these simplifications, the system becomes a combination of the moments of inertia about the motor spindles \( I₁ \) and \( I₂ \), the end-effector inertia due to \( m₃ \) and friction with coefficients \( \beta_{a₁}, \beta_{a₂}, \beta_{a₃} \), which are written as a linear function of a parameter vector \( p \) as follows:

\[
\tau = \Psi p,
\]

\[
\Psi = \begin{bmatrix} \dot{q}₁ & 0 & J^T \ddot{x} \\ 0 & \dot{q}₂ & 0 \\ 0 & 0 & \text{sign} \dot{q}₂ \end{bmatrix} \begin{bmatrix} 0 & \dot{q}₁ & 0 \\ \dot{q}₂ & 0 & 0 \\ \text{sign} \dot{q}₂ & \dot{q}₂ & 0 \end{bmatrix},
\]

and to compute \( \Psi(q, \dot{q}, \ddot{q}, \dddot{x}) \) we differentiate \( \dot{x} \) to obtain \( \dddot{x} \) as follows:

\[
\dddot{x} = J(q) \dddot{q},
\]

\[
\dddot{x} = J(q) \dddot{q} + J(q) \dddot{q}.
\]

This model was used to provide feedforward dynamic compensation using the measured or estimated shoulder motor angles, angular speeds and angular accelerations.

### 4 Mechanatronic Design

#### 4.1 Mechanical Implementation

##### 4.1.1 Pantograph

The two shoulder actuators (Kollmorgen D062M-12-13101 direct-drive brushless 2 kW servomotors) are mounted on a 12 mm thick aluminum plate. The maximum torque output per motor for this configuration is \( \sim 9.8 \) Nm in constant mode, \( \sim 32.8 \) Nm peak, providing a theoretical force output of at least \( \sim 54 \) N (at the limit of the workspace, with high Jacobian matrix condition number) and \( \sim 180 \) N constant at the center of the workspace. The two motors are placed side by side at a distance of 300 mm. Rigidly attached to the each motor’s shaft is a 262.5 mm long carbon fiber tube. At the distal end of these tubes, two longer carbon fiber tubes (450 mm) close the kinematic chain, creating a closed loop 5R topology. All four tubes are composed of Dialead High Performance coal tar pitch-based continuous fiber (12 K type, grade K63712) yielding a tensile modulus of 640 GPa, a tensile strength of 2,600 MPa and an elongation of 0.4 percent. The tube has an outer square section of \( 49 \times 49 \) mm and thickness 2.25 mm. Each elbow link has a double needle bearing, pressed in an aluminum housing that slips on a stainless steel axle attached to the proximal links. In the
4.1.2 Wrist Articulation

Mounted coaxially with and directly above the left shoulder motor is a third motor (Maxon RE65 250 W providing 0.81 Nm continuous torque) driving the wrist flexion/extension mechanism via the cable transmission. The cable is a 2.5 mm diameter Techni-Cable Ltd 1.5 mm × 7 × 7 A4-AISI 316 stainless steel cable with a 0.25 mm Nylon coating. The cable is wrapped around the driving pulley (at the motor end) as well as at the wrist pulley (end-effector). At both ends, the cable is wrapped around twice and rigidly attached to each pulley to prevent slippage as shown in Fig. 3. The cable tension can be adjusted using two bolts to pull pulley #4 away from pulley #1. Increasing tension will increase friction but improve transmission bandwidth and reduce backlash.

All pulleys (Fig. 3) are backdriveable and can rotate independently with respect to the 3DOM linkages, therefore the wrist transmission mechanism is completely decoupled from the end-effector’s xy positioning system.

4.1.3 Support Structure and Display

The manipulandum is installed within a cubic support frame (Fig. 1A) of 110 × 86 × 126 cm³ preventing collision with the device, which is assembled from 45 mm extruded aluminum profile (Bosch-Rexroth). The end-point is adjusted to a height of 84 cm which provides comfortable seated operation. An integrated display system provides visual feedback to the user, collocated with the plane of the manipulandum’s motion. This display system consists of a 36 × 30 cm² front-silvered mirror mounted at a height of 102 cm, just below the user’s eye level and a downward facing 76 cm TFT display (Dell 3008WFP) horizontally mounted above the users head. The display surface and endpoint’s plane of motion are equidistant from the mirror surface resulting in the reflected image of the display appearing to lie at the same depth as the endpoint. Registration between the coordinate frames of the display and manipulandum is achieved via software calibration. Accommodation of the complete system to different subjects’ height is accomplished by adjusting the height of the chair.

4.2 Electrical Implementation

4.2.1 Device Actuation and Position Feedback

The two elbow motors are driven by a pair of AC inverter-based servo drives (AKD-B00606) rated for a continuous output power of 2 kW from a single phase 240 V AC supply. Position feedback is provided by an integrated sine encoder with a resolution of 65.5 k steps per revolution providing a maximum resolution of 0.03 mm. The wrist motor is electrically driven by a combination of a DC PWM servo amplifier (SCA-SS-70-10) and a 60-70 V 17 A DC Switch Mode PSU (TDK-Lambda AWS1000L-60). The torque output of this configuration at the motor shaft is 2.2 Nm constant, 3.7 Nm peak. Position feedback is provided by 10 k step per revolution indexed quadrature encoder (Hengstler RIS8-0). The measurement of forces and torques at the devices endpoint was achieved via a six-axis (ATI Mini 45) force/torque transducer mounted coaxially with the wrist axis.

4.2.2 Data Acquisition

Analogue voltage I/O, digital control and encoder interfaces for the robotic hardware are provided by a PCI data acquisition board (Sensoray Model 626). Interfacing to the ATI force transducer is achieved via a secondary data acquisition board (National Instruments NI PCI-6221) which was necessary to reduce noise on the transducer signal due to crosstalk with digital control and encoder signals. The two data acquisition boards are installed within an Intel Xeon W3530 2.80 GHz, 1 Gb DDR3 RAM, PC running the Microsoft Windows XP SP3 operating system. Graphics for experimental stimulation are provided via a PCI-E Nvidia Quadro FX580. Additional control and power hardware is housed in an 18U case of the left elbow a free spinning pulley for the wrist cable transmission is placed between the two links. The elbow and wrist pulleys have a single needle bearing and are sandwiched between two thrust bearings to reduce friction.

4.2.3 Safety

Safety features are provided via mechanical stops with limit switches, an emergency stop circuit and a watch-dog timer. First, to complement the mechanical stops, two limit switches are installed at the outer extremes of 3DOM’s range of motion, which cancel force demand when actuated. Undesirable range of motion conditions which are not caught by the limit switches are detected through software thresholding of the motor encoder angles. Second, the emergency stop circuit puts the system into a safe state should AC power be applied to the system unexpectedly, if the front panel switches are operated simultaneously or if the emergency stop switch is actuated. If one or more of these conditions occurs, the system is put into a failsafe mode where all AC supplies are de-energized, and the motor enables are held low. The enable signal to motor drives is provided by the logical AND of the input from the operator enable signal, watchdog timer and emergency stop circuit. The operator enable signal is provided via either a handle mounted “dead man’s” switch or foot pedal, depending on robot configuration. The watchdog circuit is implemented in discrete TTL logic and functions to provide a motor enable signal while a continuous 200 Hz-1 kHz TTL clock is provided by the servo loop running upon
the control PC. In the absence of this clock, the circuit de-asserts the enable line within 60 ms.

4.2.4 Electrical Safety

The combination of the high voltages of the motor systems and constrained human contact with the device made electrical safety of paramount importance. In addition to the individual fusing of each motor and control circuit, a combined MCB and 30 mA residual current breaker is included at the supply input. Additionally, the motor power interlock circuit is wired in series with the internal fault relays of the servo amplifiers. In this configuration, malfunction of the drives during operation or initialization will result in the immediate isolation of their AC supply. All earth connections between motor and power supply are of at least 3 mm² and doubled for redundancy. All conductive components of the robot and control cabinet are star earthed via 2.5 mm² cables.

To ensure electromagnetic compatibility, screened cables and enclosures were used throughout and the supply of each servo amplifier was connected via an LC filter (EPCOS B84112). Redundant earthing from the laboratory mains outlet is provided by two separate main supply leads. Fig. 4 shows the general electrical layout of the system depicting its primary components, interlocks and interconnects.

4.3 Software Implementation

4.3.1 Interrupt Driven Control System

The servo loop for software control of 3DOM utilizes the interrupt functionality of the Sensoray software API, which facilitates the execution of a callback function following the assertion of a hardware interrupt by the 626 board. Timely execution of the servo loop is ensured by tying this interrupt to the overflow of a hardware timer preloaded with a count appropriate to the number of clock cycles per servo loop. The multitasking structure of the Windows OS may cause instability due to clashes with higher priority interrupts (e.g., display or network devices), however this is mitigated by minimizing the number of additional background tasks and services run by the OS.

4.3.2 Manipulandum C++ Class and Template Application

The manipulandum’s control functions are abstracted by a Microsoft Visual C++ class with access to the basic functions and parameters of the servo loop (e.g., setting end point force, reading Cartesian position) provided via public methods. Lower level private methods and variables are used to implement lower level functionality (e.g., hardware access, safety systems), protecting them from inadvertent modification. The 2DOF and 3DOF operational modes of the robot are divided into two separate classes.

The primary control loop, Jacobian computation and dynamics compensation routines are included within the class. However, the initialization of the interrupt and data acquisition hardware is conducted outside of this class and their associated handles are passed to it by reference.

4.3.3 Position/Velocity Estimation

Estimation of the 2D Cartesian position of the end-effector is performed via the forward kinematic model of (1) applied to the two shoulder encoder angles. The final end-effector trajectory is estimated by a Kalman filter using a second order linear noise model. An accelerometer could be mounted and its signal can be used to improve the prediction and yield the acceleration to compensate for the inertia term in (2).
4.3.4 Dynamic Compensation

To reduce the apparent load on the operator, 3DOM utilizes active friction compensation which is provided via the dynamics model (2).

The adaptive feedforward controller (AFFC) of [25] was implemented to identify the parameter vector \( p \) yielding minimal feedback in the feedforward control scheme

\[
\Delta p = \Psi p + \varepsilon, \quad \varepsilon = K_1 e - K_2 \dot{q}, \quad e = q_d - q. \tag{4}
\]

The AFFC is a feedforward controller using a traditional PD feedback controller and a generic feedforward term that is initially set to 0. Through gradient descent of \( \varepsilon^2 \), the error of the feedback controller is used to update the parameters of the feedforward dynamic model along a cyclic trajectory.

A periodical differentiable hypotrochoidal trajectory with large acceleration changes was used for dynamic identification:

\[
x_1(t) = (R - r) \cos t + d \cos((R - r)t/r), \\
x_2(t) = (R - r) \sin t + d \sin((R - r)t/r), \tag{5}
\]

with \( R = 0.119, r = 0.047 \) and \( d = 0.071 \). This curve roughly covers the robot’s workspace. The parameter \( p \) was updated at the end of each cycle according to the learning rule:

\[
\Delta p = \Gamma \Psi^T K \varepsilon, \tag{6}
\]

where \( \Gamma \) is a diagonal matrix of learning gains.

With learning factors adjusted to give stable convergence, the parameters converged within approximately 10 seconds or three cycles, drastically reducing the Kollmorgen shoulder motors angle and angular velocity errors (Fig. 5). Within the first cycle of the learning process the end-effector tracking error improved rapidly (Fig. 5, inset). The motor angular position and angular velocity errors were calculated as \( e(t) = q_d(t) - q(t) \) and \( \dot{e}(t) = q_d(t) - \dot{q}(t) \), respectively.

The identified values of the endpoint mass \( (m_3 = 1.485 \text{ kg}) \) and the motor inertias \( (I_1 = 0.0020 \text{ kg} \cdot \text{m}^2 \) and \( I_2 = 0.0043 \text{ kg} \cdot \text{m}^2 \)) were close to the values estimated from CAD solid modeling \( (m_{3,CAD} = 1.485 \text{ kg}, I_{1,CAD} = 0.0038 \text{ kg} \cdot \text{m}^2 \) and \( I_{2,CAD} = 0.0037 \text{ kg} \cdot \text{m}^2 \)). The friction parameters were identified as \( \beta_{a1} = 0.2106 \text{ Nm}, \beta_{a2} = 0.4021 \text{ Nm} \cdot \text{rad}^{-1}, \beta_{d1} = 0.1061 \text{ Nm} \) and \( \beta_{d2} = 0.3832 \text{ Nm} \cdot \text{rad}^{-1} \). The identified friction parameters for each motor were used to compensate for the dynamics. The effectiveness of this compensation was assessed by manually moving the end-effector and wrist axis about a circular trajectory with speeds of 0-0.3 \( \text{m/s} \) and 0-100 \( /\text{s} \) for the pantograph and wrist respectively while measuring end-point reaction force/torque. With the friction compensation enabled, the measured end-effector reaction force/torque was 60 percent lower.

To prevent the system from oscillating at low end-effector velocities, the hard limit at \( \beta_d \) is smoothed by a velocity dependent sigmoid gain function which takes the value of 0 at zero velocity. This was found to provide a much smoother start to motion at the expense of a slightly increased starting torque.

4.3.5 Force Production and Measurement

Force is controlled in open loop and updated with each servo loop iteration via the Jacobian, user force demand and encoder angles. The resultant shoulder motor demand torques are added to those generated by the dynamic model before being forwarded to the shoulder motors.

Torque output is forced to zero when the end-effector leaves the useable workspace, the wrist angle approaches a physically uncomfortable extreme or the limit switches are actuated. On resumption of a safe condition, torque production is ramped back to the demand value over a period of 200 ms.

The ATI data acquisition and calibration matrix were implemented within the 3DOM control class using the ATI supplied ATIDAQ C libraries [26] in combination with the National Instruments DAQmx ANSI C libraries. The transducer measurements are sampled by the data acquisition system once per servo loop and used to provide feedback for the wrist control scheme as well as per experimental requirements. As the \( x_1 \) and \( x_2 \) axes of the transducer rotate about the wrist axis the wrist encoder angle is used to transform the raw \( xy \) force and torque measurements into the robot’s co-ordinate frame.

4.3.6 Torque/Angle Control of Wrist

The wrist axis is decoupled from the pantograph and is controlled by an independent controller. This controller handles the production of user demanded torques and minimizes parasitic torques due to friction and inertia, improving backdriveability and reducing the influence of its dynamics upon operator behavior. A conventional PID feedback controller combined with a feedforward friction compensation model is used in this role and allows for either constant angle or constant torque operation. The integrator term in the PID is utilized to reduce proportional droop when non-zero set angle/torques are demanded. The effects of integral wind-up are reduced by a constant loss factor and range limit. Preliminary tuning of the control gains was conducted using the Ziegler-Nichols method and then manually adjusted to optimize the response.
5 Performance

This section describes tests to characterize 3DOM’s force production capabilities, position resolution, range of motion and dynamic response.

5.1 Timing Stability

The stability of the servo loop’s execution rate was tested over several different operating conditions (e.g., with OpenGL graphics, force field generation and dynamics compensation selectively enabled) against the internal 2 MHz time base of the S626 card. The loop execution period was measured by recording the difference of an internal hardware counter between cycles at the demand signal update stage of the loop. Over all conditions the loop averaged a period of 1 ms with 97 percent of cycles in the range 0.9 to 1.1 ms.

5.2 Measured Force/Position Resolution and Limits

Positional accuracy was assessed using an external optical measurement device (Atracsys Easytrack 500) with LED markers attached to the robot body and end point for coregistration. By comparing position measurements from both devices the average accuracy of 3DOM was found to be 1.60 ± 0.16 mm over the entire workspace. The accuracy of the optical system was quoted as 0.2 mm over the volume used. Errors in endpoint estimation are attributed to the combination of inaccuracies in registration of the optical system and flexibility of the pantograph structure.

Using the integrated force/torque transducer the device was found to be capable of producing a minimum isotropic force of 55 N over the entire workspace, and a peak force magnitude capability of 108 N at \( x_1 = 0 \) cm, \( x_2 = -33.5 \) cm (Fig. 2A).

The maximum static torque produced by the wrist mechanism was 2.13 Nm constant and 3.68 Nm peak, regardless of the end-effector’s \( x_1, x_2 \) position. The inbuilt thermal protection of the wrist servo amplifier limited sustained peak output to a maximum of 200 ms before clamping the output to the continuous value (fold-back). As this exceeds the manufacturer’s rating of 0.83 Nm continuous torque for the wrist motor, a secondary software mechanism restricts operation at this level beyond a few seconds.

5.3 Wrist Motor Friction

As the dynamics of the wrist articulation are excluded from the model of (2) its friction characteristics were established experimentally. This was performed with the cable and end-effector coupled to the motor. Due to the limited angular displacement of the end-effector, a low frequency square torque demand signal of gradually increasing amplitude was used to drive the end-effector back and forth between the limits of its travel. The friction model \( \tau = \beta_\alpha \text{sign}(\dot{q}) + \beta_d \dot{q} \) was then fitted for the peak angular rate for each half cycle of the demand signal. The friction parameters were identified as \( \beta_\alpha = 0.121 \) and \( \beta_d = 0.025 \), with \( R^2 = 0.992 \) (Fig. 6).

5.4 Performance

The mechanical bandwidth of the pantograph was assessed by measuring the force produced at the end-effector blocked at 3 \( \times \) 4 locations over the workspace. At each location a sinusoidal force signal of peak amplitude 10 N was applied in the direction of the \( x_1 \) and \( x_2 \) axes, ramped in frequency between 0.5 and 100 Hz at a rate of 1.7 Hz/s. The system gain was estimated as the ratio of force magnitude measured at the end-effector to the demand force magnitude for each step of the frequency ramp (Fig. 7).

The average gain was found to be approximately flat up to 15 Hz for the entire workspace, largely accommodating the 2 Hz bandwidth of voluntary motion expected about the elbow [27]. The two (~10 dB) resonant peaks which occur at approximately 30 and 45 Hz are attributed to the resonance of the support frame and the pantograph mechanism. The angular dependence of these peaks was established by rotating the direction of the force demand signal through 360 degree in 10 degree increments in the plane of the workspace. For each angle the drive signal was ramped in frequency. The inset in Fig. 7 shows the gain at the two peaks as a function of rotation angle. It is noted that the peak gain of the ~30 Hz components approximately coincides with the direction of independent torques acting about the shoulder motors.

Bandwidth of the wrist articulation was assessed by measuring the blocked torque while a sinusoidal demand signal of 0.5 Nm amplitude was ramped between 0 and 140 Hz. The frequency spectrum of the measured torque was estimated using a sliding Hamming windowed Fast Fourier
Transform and revealed resonant peaks at 104 and 120 Hz. We attribute the first peak to the resonance of the cable in the drive system and the second to the combined structural resonance of the robot. The response was approximately flat over the 0-50 Hz range, providing a useful bandwidth in excess of the ~2-3 Hz of voluntary wrist movements [28]. The accuracy of the endpoint force production was verified by static tests using a hand dynamometer, which indicated that actual force production magnitude error was better than 10 percent over the workspace.

6 Experimental Applications

Three simple experiments with one subject were devised to illustrate the capabilities and advantages presented by this novel interface, its dynamic characteristics and redundant wrist axis.

6.1 Effect of Joint Force Field

With 3DOM, it is possible to generate a torque field specific to one or multiple upper limb joints without the need of an exoskeleton with actuators at each joint. The wrist flexion/extension joint is directly driven by the third actuator. The shoulder and elbow joint can be actuated indirectly, through the wrist endpoint, by projecting the endpoint force using relevant Jacobians. Let the relation between joint torque be described in the human subject as $\tau_H = J_H(q_H)^T F$, where $\tau_H$ is the vector with desired torque at the shoulder and elbow, $J_H(q_H)$ is the $2 \times 2$ Jacobian, which depends on the specific subject's kinematics, and $F$ the endpoint force. Similarly, the desired force $F$ can be generated by producing torque $\tau_R = J(q_R)^T F$. Note that the robot Jacobian $J$, defined in Section 2.1, is distinct from the human arm Jacobian $J_H$. These two equations yield:

$$\tau_R = J^T J_H^{-T} \tau_H,$$

which specifies which torque the robot must produce to realize a desired torque field.

To assess the joint based force field capabilities of 3DOM we tested the following redundant reaching task. During this experiment, the subject's head and shoulder were resting against padded supports placed on the structure supporting 3DOM. This prevented the subject's torso from moving. The subject's dominant hand drove the end-effector as shown in Fig. 1C. The computer monitor displayed two fixed concentric circular sectors and an intermediate dashed circular line (Fig. 8A). The radius of the intermediate arc is proportional to the normal distance from the subject's shoulder joint to its wrist joint, estimated from the subject's forearm and upper arm lengths. As the wrist gets closer to the shoulder, the radius of the intermediate arc becomes smaller, corresponding to the radial wrist position.

The redundant task consisted in driving the wrist (represented by the dashed arc) from the start area to the finish area as fast as possible.

The protocol consisted on two separate sessions of equal structure and same number of movements: Pre ($\times$50), Torque Field ($\times$100), Post ($\times$100). In the Torque Field, (one of) the elbow or the shoulder was affected by damping implemented as described by Eq. (7). The effect was similar to moving the affected joint in a dense viscous muddy medium. No torque was applied during Pre and Post. As the purpose is merely to illustrate the possibilities of the 3DOM interface, we report here only the results of one subject (healthy male, 34 years old).

Fig. 8B shows the endpoint trajectories of the subject who performed the experiment. We observe how the elbow torque damping attenuates the elbow movement and the trajectory follows an arc centered at the shoulder. Similarly, shoulder force field reduces the shoulder movement, which makes the trajectory resemble an arc centered at the elbow. The five subjects who tested this procedure had similar results, demonstrating the possibility of implementing torque force fields using the 3DOM robotic interface rather than an exoskeleton.

6.2 Influence of Wrist Angle on Sensitivity to Curvature

To illustrate the difference between a 2DOF and our 3DOF planar interface, we let a subject (male, 34 years, right handed) explore haptic walls of different curvatures with the right hand in the mediolateral direction. The subject entered the perceived direction of curvature as convex or concave using the keyboard in a two-alternative forced choice paradigm.

The haptic walls were sinusoidal half cycles with a half-wavelength equal to the comfortable reach of the subject (40 cm) and amplitude dependent upon the desired
curvature. The subject tested these surfaces over two conditions: with the angle of the wrist articulation following the tangent of the curve, or with the wrist fixed parallel to the movement direction (Fig. 9). No visual feedback was provided during the surface haptic exploration session consisting of two normally distributed sequences of 500 randomized 6 second trials per condition about a mean established by a preliminary probe session. During each trial a curve was presented at the center of the workspace with the participant’s initial wrist center at constant distance of 5 cm from the curves peak/trough. An approximately constant 0.4 m/s speed of traversal was encouraged through visual signals of “faster” or “slower” between trials.

Fig. 9A shows typical trajectories of the subject’s exploration along a convex wall. The relative frequency of a ‘convex’ response is plotted in against curvature in Fig. 9B, for both conditions. The sigmoid function is fitted for each series approximating the psychometric function. The plot shows an approximate 2.5 times increase in sensitivity for 25 and 75 percent thresholds from the fixed to variable condition. A small bias of approximately –0.5 cm is noted in both conditions at the 50 percent chance threshold. These results suggest how the wrist orientation influences the sensitivity of discrimination of curvature, illustrating the importance of an interface which enables us to control it.

6.3 Control of Target Orientation with Wrist Angle Guidance

As a further example of the haptic capabilities of 3DOM to investigate redundant movement, we recreated a spray painting task in which subjects operate a spray paint nozzle to deliver paint evenly to a cylindrical surface. In this setup, paint is applied most effectively onto the surface when the nozzle is perpendicular to the target surface (Fig. 10). Additionally, we define the exposure index distribution (EID) as the standard deviation of EI across all sections. If the paint is applied homogeneously throughout all sections, EID is high. The exposure rate was 0.2 s⁻¹, therefore it required 5 seconds to fully expose each triangular section.

We used the mean of the exposure index and its distribution to assess the finish quality of the painted surface and the spectral arc length metric (SAL) of [29] to assess the quality of the wrist movements’ smoothness, which is a robust metric to evaluate motor learning, development and motor recovery.

The task consists in delivering the most amount of paint homogeneously across all sections in 20 seconds, therefore it was not possible to reach the maximum exposure index across all sections (EI = 1).

Two conditions were tested: orientation guidance and free movement. In the orientation guidance mode, the wrist flexion/extension angle was guided towards the correct orientation (depending on the subject’s wrist xy position) by a soft PID controller. The control gain was ramped at the start and end of the trial to prevent sudden motor commands. In the free movement mode, the subject freely and independently moved the xy position and the orientation of the nozzle, with no assistance from the robot.

We report here the results of one healthy subject (male, age 32) who performed 38 randomized trials. The total number of trials for unassisted and assisted movements was 16 and 22, respectively. The goal of the simulation was demonstrated to the subject prior to testing.

EID and SAL failed the Shapiro-Wilk normality test on both conditions (p < 0.05). The Mann-Whitney test (MW) was performed to compare differences between both conditions. In all tests, the confidence interval was 95 percent.

There was no significant difference in mean exposure index EI between both conditions. Nevertheless, the guided wrist movement trials presented more uniform distribution.

Fig. 9. Example of endpoint trajectory with varied curvature and wrist angle for the two conditions of the experiment (A). Psychometric functions and raw response frequencies of exploration of a curved surface for fixed and variable wrist orientation axis conditions. The sigmoid function fitted to each curve is shown as a dashed line (B).

Fig. 10. Exposure experiment setup. The triangle represents the paint nozzle. The dashed line represents the direction of the paint. The nozzle can move in xy and can rotate. When the nozzle is perpendicular to the tangent of the target’s surface, the arc polygons become exposed. The exposure index (0 < i < 1) for a given polygon increases proportionally as a function of time exposure (A) Wrist flexion angle error over time with and without assistance (B, top). Wrist flexion movement spectral decomposition of the assisted and unassisted trials (B, bottom).
compared to the free movement trials \( p_{\text{new}} < 0.02 \) and were significantly smoother \( p_{\text{new}} < 0.01 \). The spectral frequency decomposition analysis of the assisted movements displayed a lower amplitude and range in the frequency domain, which is an indication that the assisted movements were more continuous and less complex. This illustrates the capability of 3DOM to investigate the control of redundant planar movements.

7 DISCUSSION

This paper described the design, implementation and testing of 3DOM, a 2D parallel manipulandum with an additional powered wrist articulation. It was shown that the device can safely generate large forces and apply fast changes of dynamics over a large workspace corresponding to the arm reaching about the shoulder. The redundant safety features implemented in the hardware and software minimize the risk of 3DOM harming its user.

The device has little inertia and includes an active friction compensation algorithm, thus yields low impedance during movement. A unique advantage of 3DOM is its ability, with appropriate torso restraint, to completely constrain the position and orientation of the arm including wrist flexion/extension. Furthermore, due to its lightweight wrist handle, 3DOM is capable of generating high bandwidth forces to the wrist end-effector.

The 3DOM compares favorably to other existing interfaces, providing superior force production to the majority of four bar linkage based devices such as [13], [14], [17]. The mechanism is also still due to its parallel structure and careful design. Additionally, because of the symmetry of its structure and the placement of the end-effector directly on the front joint of the linkage, 3DOM has excellent homogeneity of force production with its singularities kept at the extremes of the operator workspace. Although other interfaces have provided torque generation capabilities about the wrist [13], [17], to our knowledge this is the first interface capable of completely constraining the posture of the arm and wrist flexion (as was illustrated in the example applications) while simultaneously maintaining good back-drivability and torque production.

This capability puts 3DOM at a unique advantage to investigate how individual joints and muscle groups are recruited in a carefully controlled environment. Furthermore, 3DOM enables, using the Jacobian relating the robot endpoint force and the individual joint torques of the arm, to apply joint specific constraints and force fields, as was illustrated in a demonstration experiment. This eliminates the need for an exoskeleton and mechanical adaptation to accommodate differing limb lengths of users.

The novel rigid and lightweight handle allowed for a stiff connection between the actuation and the wrist. The subject’s fingers and palm were rigidly attached to the support, which may enable a good estimation of wrist flexion/extension joint impedance. Yet, no discomfort was reported from over 100 users with different hand sizes. Additionally, it took less than 2 minutes (on average) to replace the right hand handle with the left hand handle. This modularity makes this detachable handle an excellent interface for other devices supporting wrist flexion/extension, e.g., [30].

The experiments presented in this paper show that the 3DOM robotic interface is capable of generating high force levels at high bandwidth and applying them at the individual human arm joints while preserving the safety of the user.

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