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A Hybrid Hydrostatic Transmission and Human-Safe Haptic Telepresence Robot

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Abstract— **We present a new type of hydrostatic transmission that uses a hybrid air-water configuration, analogous to N+1 cable-tendon transmissions, using N hydraulic lines and 1 pneumatic line for a system with N degrees of freedom (DOFs). The common air-filled line preloads all DOFs in the system, allowing bidirectional operation of every joint. This configuration achieves the high stiffness of a water-filled transmission with half the number of bulky hydraulic lines. We implemented this transmission using pairs of rolling-diaphragm cylinders to form rotary hydraulic actuators, with a new design achieving a 600-percent increase in specific work density per cycle. These actuators were used to build a humanoid robot with two 4-DOF arms, connected via the hydrostatic transmission to an identical master. Stereo cameras mounted on a 2-DOF servo-controlled neck stream live video to the operator's head-mounted display, which in turn sends the real-time attitude of the operator's head to the neck servos in the robot. The operator is visually immersed in the robot's physical workspace, and through the bilateral coupling of the low-impedance hydrostatic transmission, directly feels interaction forces between the robot and external environment. We qualitatively assessed the performance of this system for remote object manipulation and use as a platform to safely study physical human-robot interaction.**

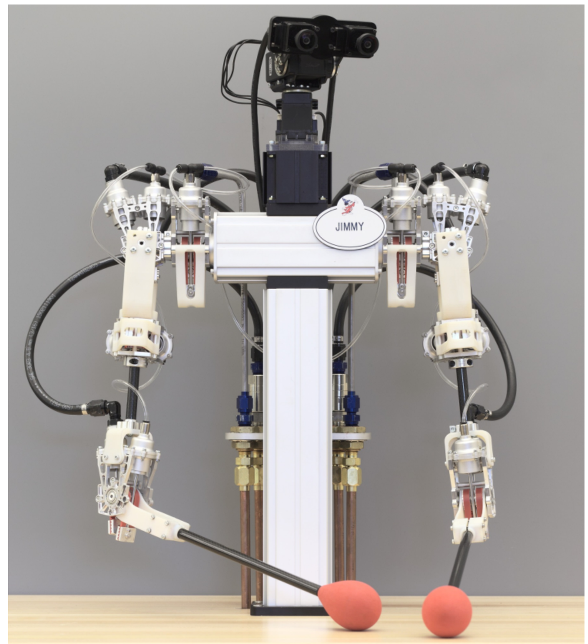

Fig. 1. This robot has two 4-DOF arms (serial *RRR* shoulder and *R* elbow), with a pair of cameras mounted to a 2-DOF neck formed by a pair of Dynamixel MX-106 servos. The arm actuators are coupled to an identical control figure behind the wall through an N+1 hybrid hydraulic-pneumatic transmission using rolling-diaphragm actuators.

I. INTRODUCTION

Remote manipulation has a long history, beginning with the original mechanical master-slave telemanipulators developed by Goertz to handle nuclear materials. These early machines provided a direct mechanical connection between the operator and manipulator using cables and linkages. These systems were quickly extended though the use of servomotors and servohydraulics [1]; with the addition of force sensors, closed-loop electronic control, and head-mounted displays, the modern telemanipulation system was born.

The challenges of achieving high quality bilateral force reflection and low mechanical impedance for these systems is closely related to the challenges faced in developing robots safe for direct physical interaction with humans. Indeed, the design approaches taken in advanced cable-driven robots [2]–[4] directly trace their history to these original master-slave manipulators. An essential component in many human-safe robot and telemanipulator designs is the mechanical transmission, used to reduce moving mass and limb inertia, allowing stiff, high-bandwidth operation, and minimizing, as much as possible, overall mechanical impedance. Series-elastic designs are further improving performance by allowing high impedance torque sources with low mass to be used safely [5].

In addition to cable-tendon transmissions, hydrostatic transmissions offer an interesting solution to this problem. Challenges with fluid leakage, seal friction, and losses from fluid damping are offset by the relative ease in routing flexible hydraulic lines; hydrostatic transmissions are particularly suited to serial robot arms with many degrees-of-freedom. Their use has recently been expanding, finding applications in MRI-compatible remote manipulation [6], robot arms [7], and rehabilitation robotic devices [8].

In this paper, we present a new type of hybrid hydrostatic transmission that mixes hydraulic and pneumatic lines, allowing stiff, independent control of every joint, with global control over transmission preload pressure, similar to an N+1 cable-tendon transmission. We have developed new rotary actuators using rolling-diaphragm cylinders which provide high torque density, and allow the creation of a

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new high-performance 10-DOF humanoid robot (figure 1), configured as a master-slave remote manipulator. This system is designed as a testbed to study human-robot interaction, and provides the operator with high quality haptic information, directly transmitted through the N+1 hydrostatic transmission. We make a careful comparison between pneumatic, hydraulic, and hybrid transmission configurations, and present detailed results in the accompanying video on the qualitative performance of the robot, including demonstrations of delicate object manipulation, needle threading, and safe interaction with people.

II. HYDROSTATIC TRANSMISSIONS

Contrary to traditional valve-based hydraulic systems, hydrostatic transmissions provide a direct fluid coupling between an energy source/sink—most commonly an electric motor—and a remote joint. This approach is often heavier and bulkier than traditional hydraulics, because each motor must be sized for the maximum joint load, and the use of many smaller motors forgoes the beneficial performance scaling of using a single larger motor to drive a hydraulic pump. However, a hydrostatic transmission has the singular advantage of offering very low impedance. In the simplest configuration, two hydraulic cylinders are connected together, and a low-friction direct-drive motor is connected to the input cylinder [9]. The heavy motor no longer must be carried when used in a serial-link manipulator, reducing moving mass and limb inertia. Because the transmission is fluid based, flexible hydraulic lines and hydraulic swivels make routing many degrees of freedom through a single joint possible.

A. Rolling-Diaphragm Rotary Actuators

Rolling-diaphragm cylinders avoid the tradeoff between seal friction and leakage when using a sliding rubber o-ring or cup-seal to seal a hydraulic cylinder piston and rod. Zero leakage and low static friction come at the expense of a lower operating pressure. This limitation is not significant for applications that place hydraulic manipulators in close proximity to people, due to existing safety limits on operating pressure resulting from stored energy hazards (pneumatics) and pinhole leak hazards (hydraulics). Their low operating pressure excludes rolling-diaphragm cylinders from high-powered industrial hydraulics.

With a continuous diaphragm, the operating fluid is not required to lubricate any sliding seals, so it is feasible to use water or water-based fluids instead of oil. The low viscosity and high bulk modulus of water provide lower fluid damping, higher transmission stiffness, and higher operating efficiency. Rolling-diaphragm hydrostatic transmissions have recently become popular for use in robot arm counterbalances [7], haptic manipulators [10], and rehabilitation devices [8].

Figure 2 illustrates a traditional rolling-diaphragm cylinder, and shows the specific cylinders used in this work. A positive pressure differential across the diaphragm must always be present to prevent inversion and jamming of the diaphragm. For this reason, practical actuators must use two diaphragms in an antagonist rotary, or double-acting linear configuration, to allow bidirectional transmission of torque [10].

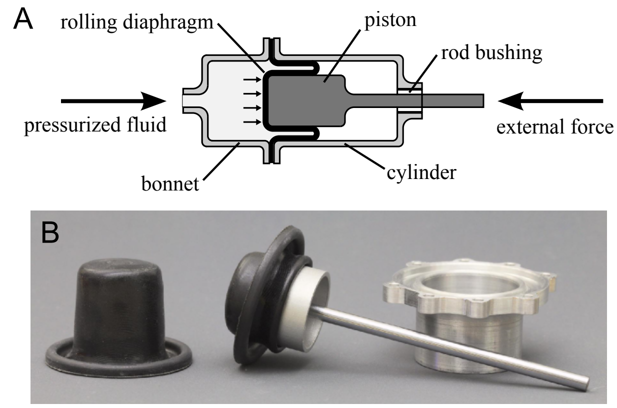

Fig. 2. **A** Diagram of a rolling-diaphragm cylinder. Contrary to a normal hydraulic cylinder, there is a sizable gap between the piston and cylinder wall, allowing the inverted fiber-reinforced diaphragm to roll from cylinder to piston, and vice versa. **B** The fabric-reinforced nitrile rubber diaphragms used are IER Fujikura part number DM3-20-20, with a 24 mm stroke, for a 20 mm bore cylinder, withstanding a maximum operating pressure of 1.7 MPa (250 psi). A molded-in o-ring at the base of the diaphragm is clamped by the cylinder bonnet into a groove integral to the cylinder flange.

The configuration adopted here, and employed previously in [10], uses cylinder pairs, balanced 1:1 with timing belts. A pair of belts is used, allowing the cylinder rods to travel between the belts and run exactly tangent to the timing belt pitch diameter. Figure 3 shows a partial cutaway view of the new design. Particular care was taken to remove any extra mass from the cylinders and actuator housing. The cylinders are angled inward to allow a smaller timing belt pulley and maximize the actuator range of motion. The timing belt pulley has dual integral 8 mm shafts to output rotary motion.

We discovered that the timing belts provide a stabilizing restoring torque when the cylinder rod is pushed sideways, which combined with the lateral stability of the rolling diaphragm, allows operation of the rotary actuator without any cylinder rod guide bushings. As the timing belts will never track in exactly the correct position, eliminating the bushing removes bushing side-loading of the rod, reducing actuator friction. These actuators use high-strength Brecoflex SFX timing belts with an AT3 tooth profile and steel-cord reinforcement.

The previous design for a rolling-diaphragm rotary actuator presented in [10], delivered 2.7 Nm of torque, over a 75° range-of-motion, weighting 246 grams, giving a specific work density per cycle (unidirectional) of 14.4 J/kg. Figure 4 shows the actuator reported here, machined and assembled. It has a maximum continuous torque rating of 4.5 Nm, a 135° range-of-motion, and weighs only 120 grams, for a specific work density per cycle of 88.4 J/kg, a 600% improvement over the previous design in [10].

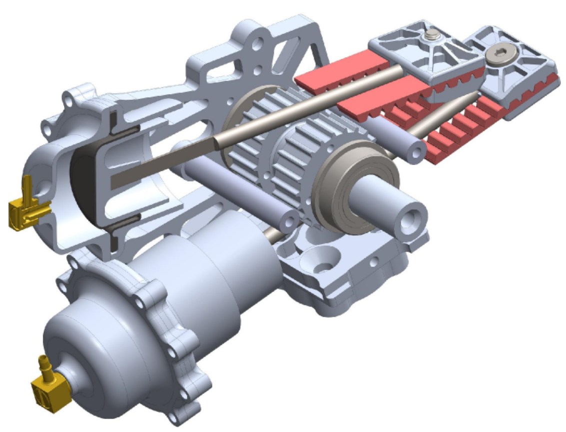

Fig. 3. (color) A 3D partial-cutaway view of the bidirectional rolling-diaphragm cylinder rotary actuator. The cylinders are angled inwards to maximize angular range-of-motion given the limited 24 mm stroke. The cylinders are balanced with a 1:1 timing belt arrangement; the split timing belt pulley has integral 8 mm shafts, providing rotary motion output. This example illustrates cylinder bonnets configured for a 2N pneumatic transmission configuration.

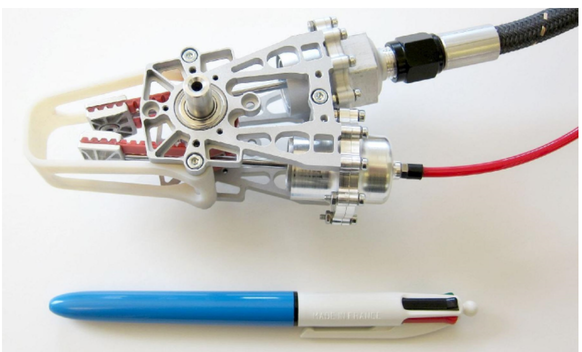

Fig. 4. (color) Photograph of the machined and assembled actuator. Maximum continuous torque is 4.5 Nm, range-of-motion is 135°, and total mass is 120 grams. Shown are cylinder bonnets configured for an N+1 hydraulic transmission configuration.

B. Hydrostatic Transmission Configurations

Bidirectional hydrostatic transmissions traditionally use two hydraulic lines to connect the input and output actuators, allowing full bidirectional torque output. This configuration is shown in figure 5-A, where pairs of cylinders are connected together with the same fluid in both lines. Thus, a system with N actuators will have a total of 2N hydraulic or pneumatic lines. To minimize the number of bulky hydraulic lines, it was previously proposed to use an external constant-force spring at each endpoint actuator to preload the hydraulic fluid in a single hydraulic line [9]. Typically the preload pressure is chosen to be one-half the maximum system pressure, giving a bidirectional torque capacity of $\pm\frac{1}{2}\tau_{2N}$, where τ_{2N} is the original torque rating of a 2N transmission. Although the maximum torque and transmission stiffness are cut in half, the fluid damping and added inertia are also halved. Unfortunately, constant force springs are bulky and have low energy density.

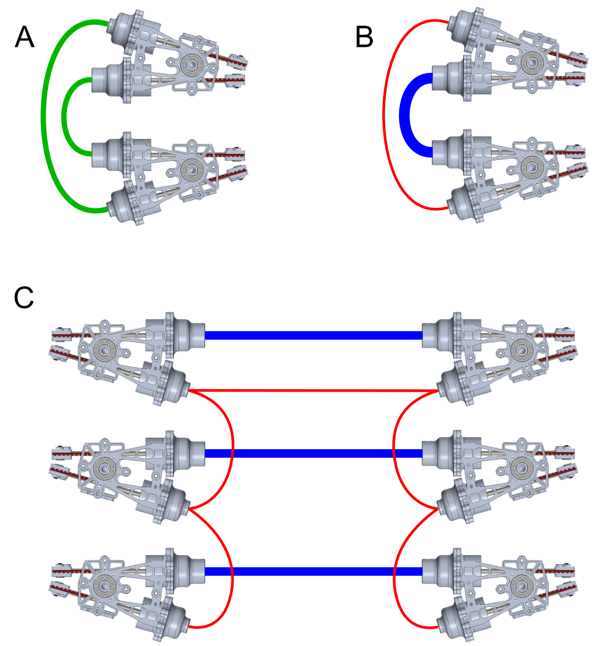

Fig. 5. (color) In configuration **A**, identical fluids are used for each pair of lines connecting the antagonist cylinders together in a 2N configuration. In **B** the N+1 hybrid configuration is shown for a single DOF, with the air line in red and the water line in blue. A 3-DOF system is shown in **C**, with a daisy-chain connection between all six air cylinders.

An alternative configuration is shown in figure 5-B. Here, one cylinder in each actuator is connected with a hydraulic line as before, but the antagonist cylinders are connected with an air-filled line. Since water is virtually incompressible, the volume in the air line will also remain constant, regardless of the position or output torque of the actuator. Pressurizing this line effectively creates a constant force air spring to pre-compress the hydraulic line. Compressed air is more mass-efficient at storing energy than a mechanical spring. In addition, we gain the ability to actively change the preload pressure, if desired, and also the ability to instantly de-energize the system by venting the pneumatic line. It is even possible to introduce a small leak into the pneumatic line and maintain continuous pressure during operation with a small air compressor. This way, if the system loses electrical power, it will passively de-energize; this might be desirable for very critical applications in remote surgery and manipulation.

If there are multiple degrees-of-freedom in the system, the air cylinders can all be connected together, daisy-chain fashion, as shown in figure 5-C. Because the hydraulic lines are filled with an incompressible fluid, the volume in the shared air volume will remain constant. There is a direct analogy in this arrangement to the N+1 type of cable-tendon transmission, which allows arbitrary position control of N pulleys with N tendons, and control of overall preload tension with the additional tendon [11].

Figure 6 shows, theoretically, how line gauge pressures respond to external torques for both the 2N (plot A) and N+1 (plot B) configurations. In the 2N configuration, the fluid in each line is the same, and the stiffness of the

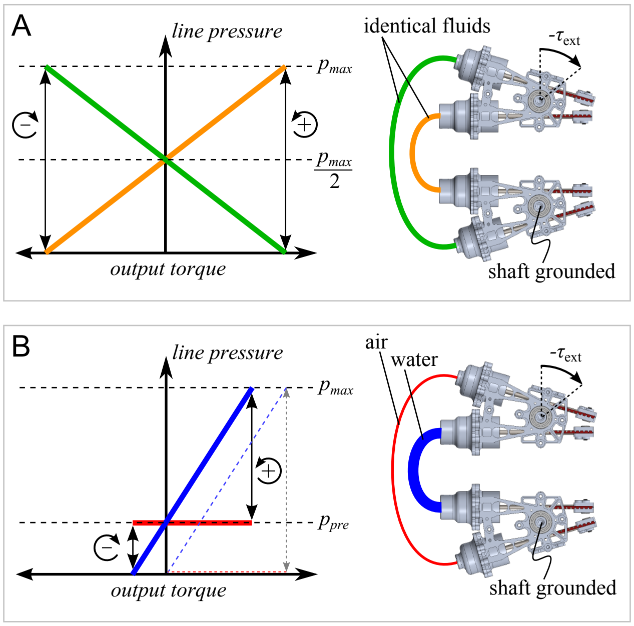

Fig. 6. (color) In these examples, one transmission shaft is grounded, and the other is loaded with an external torque, prompting pressure changes in the fluid lines leading to an equal and opposite reaction torque from the transmission. Graph **A** shows the pressure-torque profile for a 2N transmission, with both lines filled with either air or water. Graph **B** shows the N+1 hybrid configuration where one line is filled with water (blue) and one with air (red).

transmission lines (their resistance to volumetric expansion under a pressure rise) is equal. To ensure that the diaphragms do not jam, the fluid in both lines must be pre-pressurized to one-half the maximum system pressure (usually limited by diaphragm and hose bust limits).

The transmission illustrated in figure 6 has one transmission shaft grounded, and the other loaded with an external torque. For the 2N transmission, the pressure response in the two lines is equal and opposite, and when the pressure in one line reaches zero gauge pressure, maximum torque is developed, proportional to p_{max}. For an arbitrary external torque, the equal and opposite actuator torque is proportional to the difference between the green and orange curves.

But in the hybrid configuration with N+1 plumbing, the pressure in the air-filled side remains virtually constant. The stiffness of the compressed air is orders of magnitude less than compressed water, so significant changes in pressure will only result from a significant change in volume, which is inhibited by incompressible water in the hydraulic lines. Since the pressure in the pneumatic line does not change, the maximum output torque is reduced by half. However, in this configuration it is not necessary to preload the system to half the maximum pressure. Indeed, if the joint being driven has an asymmetric torque requirement (e.g. it needs to be stronger in flexion than extension), then the penalty of this configuration is less than half. In the extreme case of a joint that is only actuated in one direction, with zero preload the transmission can deliver the full torque τ_{2N}.

The N+1 configuration offers a tremendous savings in the number of required hydraulic and pneumatic lines, making it well suited to multi-DOF systems.

III. TELEPRESENCE ROBOT DESIGN

The rolling diaphragm actuators and transmission system were designed specifically for creating lightweight, human-safe robot arms. Low actuator impedance and high torque density are essential to achieving this goal. Figure 1 shows the most recent robot developed using this transmission system. Four actuators are serially connected with an *RRR* shoulder and *R* elbow. The base actuator axis is aligned horizontally in the frontal plane, which keeps the singular configuration for the shoulder at the edge of the arm workspace. Since the actuators only have a 135° range-of-motion, the arm does not match the full range of a human arm, but the workspace is sufficiently large to perform many tasks.

We built and tested a single arm first with a 2N pneumatic transmission, and then two arms with an N+1 hybrid hydraulic transmission, as shown in figure 7. While these arms are passive, the use of a hydrostatic transmission allows the easy replacement of the input ("Waldo") arms with electric motors at each transmission input actuator. Because these motors will be mounted in the base or torso of the robot, there will be greater freedom to select motors and gearing with very low friction, quiet operation, and little backlash, preserving the low impedance and easy backdrivability desired for a high performance, yet passively-safe human-compatible system. In addition, there are many interesting applications in which the passive, non-motorized, master-slave configuration would be preferred, including hazardous material handling or remote surgical manipulation (inside an MRI machine, for example). With the hydraulic version in particular, the direct transmission of haptic force information to the operator is highly desirable for delicate tasks requiring high precision in both force and positional accuracy. The current system is envisioned as a tool for studying human-robot interaction, whereby a human operator is able to simulate a robot with a higher level of performance and intelligence than is possible using current technology.

The hydraulic robot has two 4-DOF arms and a 2-DOF neck carrying stereo cameras. These cameras stream live video to the head-mounted display worn by the operator, and the measured orientation of the head-mounted display is sent to the electric servomotors in the robot neck. This allows the operator to be visually immersed in the robot workspace. When standing behind the input figure and grasping its forearms, as shown in figure 7, the position of the operator's own arms closely match the position of the arms of the robot figure the operator sees through the head-mounted display. This visual and kinesthetic matching, combined with direct force-feedback through the transmission, creates a powerful sense of immersion when controlling the figure.

IV. RESULTS

The pneumatic arm and hydraulic arms are both capable of smooth, high-speed motion. The pneumatic arm cannot

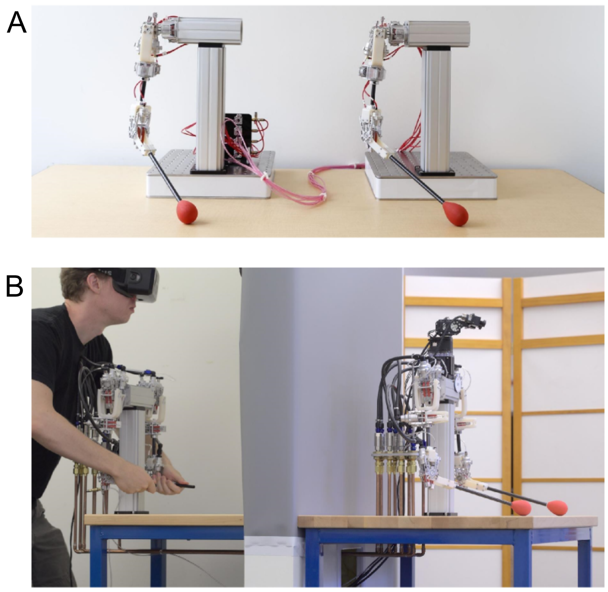

Fig. 7. (color) **A** Master-slave 4-DOF arms, configured for 2N pneumatic operation, connected by eight sections of polyurethane pneumatic tubing (95A durometer, 3.2 mm OD, 1.7 mm ID). **B** Master-slave robot with hybrid hydrostatic transmission. The two figures are separated by 1 meter, on opposite sides of a wall. Actuators are connected on each end with short sections of SAE 30R3 rubber hose to a longer middle section of hard copper pipe, except the base arm actuator in the serial chain, which is plumbed entirely with metal pipe.

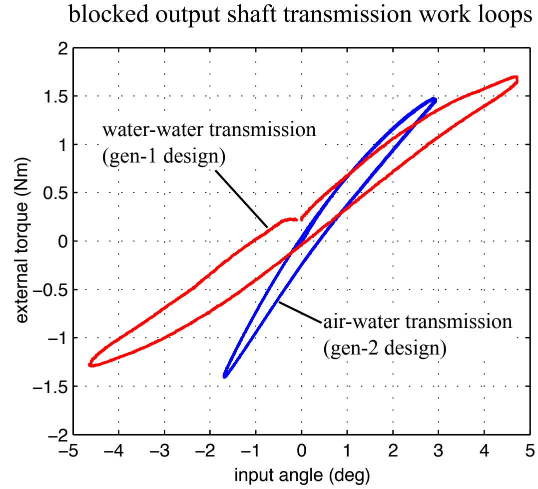

Fig. 8. (color) Comparison of blocked-output work loops of the water-water (2N) transmission design (red), as presented in [10], to the current design in air-water (N+1) operation (blue). The new design uses thinner diaphragms which allow a smaller annular width between the piston and cylinder, which proportionally reduces sidewall stress in the diaphragm, leading to an increase in transmission stiffness.

transmit high frequency haptic information to the user due to the high serial compliance resulting from air compression, and suffers from oscillation and overshoot during rapid movements, as seen in the video. Additionally, the stiffness of the pneumatic transmission is inversely proportional to the total system volume, so a large separation between the input and output is not feasible due to the increased system volume as the air lines get longer. Reducing the internal diameter, D, of the air lines to compensate is not feasible, since the viscous damping resulting from internal friction increases at least as fast $1/D^4$, so maintaining stiffness will only come at the expense of a greatly increased fluid damping [9]. However, some tasks, such as playing a percussion instrument like the glockenspiel (demonstrated in the video), require extremely low impedance, in this case to avoid deadening the sound of the instrument, and the springiness of the air transmission thus offers an advantage. The pneumatic robot also has the advantage of requiring only a simple bicycle pump to fill and pressurize the system, without the need to handle liquids or bleed air from the system.

The accompanying video demonstrates interaction with a person, bimanual object manipulation, and the handling of delicate objects, requiring simultaneous position and force control on the part of the operator. To demonstrate precision and fine motion we demonstrate remote threading of a small sewing needle, with the robot/operator looking through a stereo microscope during the task. The smoothness of motion, high power density, and utility as a testbed for human-robot interaction, is evident from the demonstrated tasks in the accompanying video, as well as the measured torque density for the current actuators, and transmission haptic qualities previously measured [10].

In figure 8 we compare the performance of the hybrid N+1 transmission (air-water) to the original 2N transmission (water-water), measuring static torque-angle work loops with a blocked output shaft. The new design is stiffer, primarily because the diaphragms chosen allow a smaller gap between the piston and cylinder. Since diaphragm sidewall loading is in proportion to this annular area, reducing piston clearance leads to a stiffer transmission. The diaphragm fabric is more finely woven, and the nitrile rubber membrane is thinner, to prevent a concomitant increase in fiber fatigue due to the reduced bending radius in the diaphragm convolution.

The 2N transmission stiffness curve is highly symmetric due to the symmetrical arrangement of dual water-filled actuators. While the N+1 version is stiffer, there is an asymmetrical softening effect observed on the tension side of the curve, possibly due to a reduction in timing belt preload, and thus timing belt rotational stiffness. The measured static friction, viz the vertical drop at the ends of the work loop, is measured to be 0.025 Nm for the new design.

We have yet to quantify the haptic performance of the two-arm hydraulic robot as a complete system. Qualitatively, the haptics of the present robot allow consistent detection by multiple human operators, by feel alone, of a step-down formed by a single sheet of notepaper (90 microns thick) pressed against the table with the carbon fiber forearm; remotely typing on a keyboard feels the same on the input as it does on the output; differentiating between an unfinished piece of plywood and a smooth plastic sheet (when blinded to sound) is easily done. These tests so far have been informal, and need to be repeated using proper human subject protocols.

Increasing the stiffness and bandwidth of the transmission will be achieved largely through an increase in hose stiffness. The use of lightweight hydraulic swivels and rigid tubing to replace all or part of the rubber hose used for distal actuators, will greatly improve transmission stiffness. The actuators and transmission, as currently designed, cannot be vacuum bled, because the diaphragms would invert and jam in the process, so the actuators must be modified to allow the application of vacuum to both sides of the diaphragm. The system is currently bled using a flow-through approach, and it is difficult to assess the amount of trapped air that remains in the system.

The rolling-diaphragm rotary actuators comfortably beat the torque density of harmonic drive servos. For example, the FHA-8C-100 from Harmonic Drives LLC provides a similar maximum torque of 4.8 Nm, but weighs 400 grams. However, the diaphragm actuators are larger in length and breadth. Reducing the volume of the actuators will require either an increase in operating pressure to use smaller cylinders, or a customized design that eliminates the need for the bulky o-ring flanges at the base of the diaphragms. The torque density of these actuators can likely be increased by moving to a monolithic composite structure, rather than the current approach of bolting together multiple CNC-machined aluminum components. We have also begun testing of a linear-actuator configuration, similar to a traditional double-acting hydraulic cylinder, with a slimmer shape that better integrates into high aspect ratio robot limbs.

V. CONCLUSIONS AND FUTURE WORK

As shown in the accompanying video, the current hydraulic robot offers incredibly smooth and fast motion, while maintaining backdrivability and bidirectional force reflection, allowing safe interaction with people, and the handling of delicate objects.

To minimize costs and complexity, all four actuators for each arm are identical, rather than being sized proportional to their expected loads. To add a wrist and hand will require smaller actuators to keep overall arm inertia to an acceptable level. Additionally, the input figure for the mechanically teleoperated version would need to be partially converted to an exoskeleton interface to allow the operator to smoothly control the additional wrist and hand degrees of freedom.

The new rolling-diaphragm actuators and N+1 configuration have enabled the creation of a high-performance humanoid robot, capable of direct mechanical teleoperation, providing visual, kinesthetic, and haptic immersion for the operator. It is under active use as a testbed to study human-robot interaction, and for testing the importance of haptic and visual cues for remote manipulation task performance.

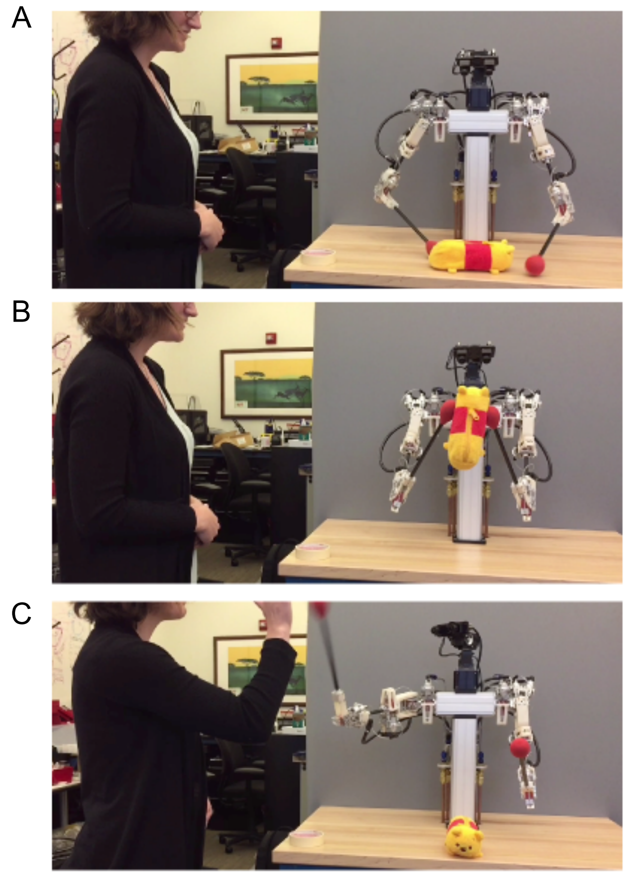

Fig. 9. (color) In **A** and **B** The robot, teleoperated, with the operator behind the wall wearing a head-mounted display, turns, picks up, and manipulates a small plush toy. In **C** the robot gives a "high five". These three images are stills from a video recording of operation of the robot.

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