J Intell Robot Syst (2017) 85:413–429
DOI 10.1007/s10846-016-0392-6

Novel Haptic Device Using Jamming Principle for Providing Kinaesthetic Feedback in Glove-Based Control Interface

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Received: 21 December 2015 / Accepted: 21 April 2016 / Published online: 15 June 2016

Abstract This paper presents a new type of wearable haptic device which can augment a sensor glove in various tasks of telemanipulation. We present the details of its two alternative designs *jamming tubes* or *jamming pads*, and their control system. These devices use the jamming phenomena to change the stiffness of their elements and block the hand movement when a vacuum is applied. We present results of our experiments to measure static and dynamic changes in stiffness, which can be used to change the perception of grabbing hard or soft objects. The device, at its current state is capable of resisting forces of up to 7 N with 5 mm displacement and can simulate hardness up to the hardness of a rubber. However, time necessary for a complete change of stiffness is high (time constant 0.5 s); therefore, additional cutaneous interface was added in a form of small vibration motors. Finally, we show an application of the haptic interface in our teleoperation system to provide the operator with haptic feedback in a light weight and simple form.

Keywords Haptic device · Haptics and haptic interfaces · Jamming · Soft robotics · Robot control interface · Human-robot interaction

1 Introduction

Using one's own hand to teleoperate a robot with a multi-finger (dexterous) gripper can be very intuitive for robot's operator. However, if the operator receives feedback about the state of grasping operation only through visual or auditory channels, he can experience sensory overload [27] and generally perform worse than when receiving a kinaesthetic feedback [7]. This can be especially important when teleoperating robots in exploratory or rescue tasks, where mistakes in grasp execution cannot be easily corrected and can lead to mission failure.

While devices for kinaesthetic feedback for grasping (e.g. CyberGrasp [1]) are available, they are not as widespread as general control interfaces, because they can be very costly (more than USD $10000) due to their complicated mechatronic structure.

In our quest to develop an intuitive teleoperation interface for controlling Schunk Dexterous Hand (SDH-2) during search and rescue operations, we investigated the use of simple haptic devices to inform the operator about the state of grasping in prolonged

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Research partially supported by the National Centre for Research and Development under grant No. PBS1/A3/8/2012 and by the Foundation for Polish Science under grant No. 132/UD/SKILLS/2015

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teleoperation. Such devices should be ergonomic, lightweight and safe for the user. Also, they should not introduce instability to the teleoperation system with possible signal delays (stability of teleoperation system as defined in [17]).

Our proposed solution uses jamming phenomena for kinaesthetic feedback – described in detail in Section 2.2. Jamming allows for change of stiffness of material in flexible membrane, controlled by pressure inside. By positioning an element with changeable stiffness on hand palm, motion of fingers can be blocked when the element is stiffened, providing a sensation of grasping an object. We describe two designs of such device, called *jamming tubes* and *jamming pads* with additional cutaneous interface placed on fingertips, and explain their controller.

We have conducted a series of experiments, to provide answers to questions connected to the device's design:

To choose appropriate filler material for the jamming device, we have evaluated the range of stiffness change for different materials, as well as maximum reaction forces generated when flexing the element.

To evaluate the feasibility of using jamming for haptics, we have conducted dynamic experiments, where we measured the time necessary for stiffness change, as well as the device's behaviour when experiencing step force change or pressure exerted by the human finger.

Finally we explore how such a haptic device could be integrated into a larger teleoperation interface for controlling manipulator with dexterous gripper. We discuss specification of such task and describe integration of the device into previously developed ROS based system [34–36].

Our idea of using jamming for kinaesthetic feedback for grasping can be used as a simple way for adding such ability to teleoperation interfaces or be a basis for other haptic devices.

2 Related Work

Our haptic interface has a number of features similar to those found in several types of haptic interfaces described in journals, and available in commercial applications.

They can be described as:

Glove Based A general review of glove based interfaces is presented in [5]. Although, our interface is not entirely glove based (there is an additional vision system for measuring the hand's position, orientation and gestural control), it can directly acquire the flexion information from all fingers and generate sensations to the user through the glove. It also has the typical disadvantages: the human hand is restricted by the glove, there is mechanical wear and the glove must be calibrated (our calibration procedure for flexion sensors was described in [36]). The commercially available CyberGrasp [1] provides force feedback through tendons routed to the fingertips via an exoskeleton, while the Exo-glove [13] is a bio-inspired system where the soft tendon routing system is used, enabling actuators to be placed further up the forearm making the glove more compact.

Multimodal Our interface is multimodal. It generates haptic sensations through more than one channel, namely by using vibrotactile and force-displacement cues. This offers better dynamic range, an ability to identify touch events, a better perception of softness and a better recognition of changes in contact conditions. A device capable of multimodal, haptic rendering during pinch grasping is presented in [32], where the authors designed the UGrip multimodal display with voice coil actuators controlling two aluminium plates.

Multifinger As most manipulation tasks engage multiple fingers, multi-contact haptic devices give a much higher realism and allow performing in a more intuitive way than simpler solutions [9]. Multiple points of contact can be provided through:

- Several robot-like haptic mechanisms (e.g. two phantom omnis) sharing the workspace and using collision avoidance [9, Ch. 1]
- *Haptic modules* – specially designed mechanical devices that can be connected together to create a single multi-finger collision-free haptic device [9, Ch. 4]
- *Haptic hands* like HIRO – a robotic hand fixed opposite to a human hand and connected through finger holders and passive spherical magnetic joints [9, Ch. 5]
- *Encountered-type* haptic mechanisms, where the user interacts with a device having changeable characteristics, which is located in the place of the virtual object being seen by the user. Modules of different shapes and function are used for this

approach in [33]. Non-grounded, *exoskeleton* and *wearable* type structures, where a structure is fixed to a human hand and forces are transferred to fingers through a set of linkages or tendons, or worn directly on fingers.

Our device can be categorised as a wearable exoskeleton, as the device is worn on the hand. Its working volume is therefore not limited by being grounded and workspace can move with the operator. It also presents similar challenges as other devices of such type i.e. difficulty to generate forces in all directions and oppressiveness because its weight always needs to be carried.

Using Jamming Phenomenon This mechanism, further described in [29] is very promising in the fields of soft robotics and soft actuators, gripper technologies and human-computer interaction. Our work is directly influenced by [8] where authors describe how jamming can be used to create interfaces. A wearable haptic display *Particle Mechanical Constraint* [19], designed to constrain movement of the shoulder and elbow has a very similar working principle to our *jamming tubes*. A comparison between these two solutions is provided in Section 3.2. Also, Jamming Mitten uses a phenomenon of layer jamming to provide a haptic feedback to user's hand [26]. In [31] authors used granular jamming to create soft robotic exoskeleton that can be worn on a back of a hand.

Passive Kinaesthetic Haptic Interface This type can generate only reaction forces but the inherent passive stability is an asset. In [23] electrorheological (ER) fluid with viscosity controllable by electric field is used to produce a passive force display system – the ER constricting movements simulates contact with virtual walls. Our interface is also able to generate reaction forces, however, it is done by changing the stiffness of the granular material or paper layers enclosed inside a rubber shell.

2.1 Benefits and Requirements for Haptic Devices

Guidelines for haptic rendering are presented in [10], while detailed implementation requirements are presented in [11, 16]. A general review of the benefits and design guidelines for using haptic devices is presented in [16]. In the case of interfaces for grasping and telemanipulation, they provide a number of benefits:

- Increased understanding and performance - experiments from [7] show that performance of grasping a ball with accurate force was increased by 52.3 % when there was haptic feedback
- Reduced completion time and number of errors - when telemanipulating a robot with force-torque feedback for putting a peg in a hole and manipulating electrical connectors [12]
- Capability of prolonged manipulation - without haptic feedback it could be very difficult for users to maintain a static hand position, because without physical support the hand may slowly relax or weaken [6]
- Reduced sensory overload as otherwise contact information that is important for grasping would need to be presented through visual or auditory channels [27].

2.2 Jamming Principle

2.2.1 Granular Jamming

Jamming of granular material is a process where a granular material, such as sand or coffee transitions from a liquid-like state to a solid-like state with a small change in defining volume. It can be defined on a physical level as a process when particles of granular media, normally behaving like fluid particles, under external forces extending over some threshold form force chains, able to support loads [4].

This jamming phenomena can be used to create useful devices through enclosing granular material in flexible membranes, with fluid (air or oil) being an interstitial material that can be pumped in or removed from between the particles. Removal of the fluid causes a pressure difference and the membrane shrinks, constricting the particles and causing the jamming process. By allowing fluid to flow back, the membrane ceases to constrict the particles and allows them to move freely again, so they can no longer support loads.

The process of granular jamming is used in a jamming gripper [8] as well as in a wide range of robotic designs: grippers, actuators, haptic displays [8, 14, 28].

2.2.2 Layer Jamming

Layer jamming, defined in [15] is a mechanism where negative air pressure (pressure in the container being lower than environmental pressure) causes change in friction between layers of material. In an unconstrained state, each layer can move freely and bend with minimal force, but with stronger vacuum, the friction between layers is increased and prevents them shearing past each other [21]. The process of layer jamming was used in a tubular snake-like manipulator [15], to create deformable interfaces [22] or in wearable haptic devices [26].

Using the phenomenon of layer jamming in comparison to granular jamming has several positive aspects, such as ease of modelling (as strength of jamming is proportional to number of layers), or the possibility of very flat elements (as even two layers could be jammed). In case of our interface, the biggest advantage is that the filler material does not become unevenly distributed and does not create empty spaces inside a membrane when being repetitively bent.

3 Description of Pneumatic Haptic Interface

In this section we describe two versions of the haptic interface – jamming pads and jamming tubes, and their controller.

3.1 Jamming Pads

First of the proposed haptic interfaces based on the idea of jamming are jamming pads. A diagram of jamming pads is presented in Fig. 1. A pad, made of latex rubber is glued to an elastic glove in the way that it is placed under the user's joint. The air is removed by a pneumatic tube.

Our device works through resisting or blocking further movement of the human joint, thereby simulating contact with a soft environment or a hard constraint, respectively. A pad can be compared to a splint immobilising finger when fully stiffened but allowing movement when soft.

The current design successfully blocks an enwrapping movement of the hand (closing the hand), but does not constrain movements in other directions. This behaviour matches the typical response to the readings of tactile sensors mounted usually on the inner side of the palm of the robot's gripper – they are detecting constraint only when closing the robot's hand.

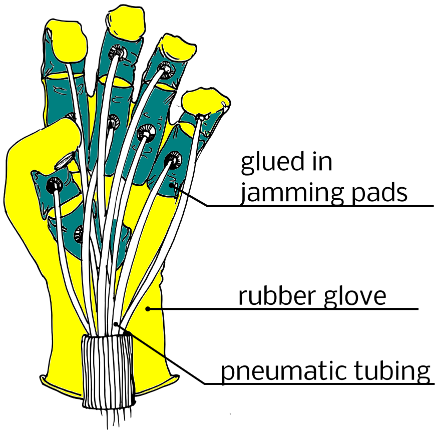


Fig. 1 Diagram of jamming pads interface

3.2 Jamming Tubes

Jamming tubes are an alternative to jamming pads, where the user has one tube with jamming material connected through harness to each of his fingers. When the force is to be displayed to the user's fingers, the tube on the particular finger stiffens through the jamming process controlled by the vacuum pressure.

Stiffened tube counteracts movement in the direction toward the tube and partially in the direction of the side harness. A user can still move in the direction opposite to the tube – releasing grip – with significantly smaller resistance, as there is only a pair of rubber bands of the harness, resisting this movement. The latter behaviour is in our opinion advantageous to the *Particle Mechanical Constraint* (mentioned earlier) where the wearable haptic display is fixed to the underarm and the wrist, and jamming it restricts any movement; therefore, the intention of "escape motion" has to be detected by additional force sensors located on the surface of the device. Similarly in [31], authors placed jammable elements on the back side of the hand, which also does not provide way for hand to open when the device is jammed. Also, the operator of such a device would not have the feeling of grasping something, but only of being constrained.

Similarly to *Particle Mechanical Constraint*, granular material in tubes could become unevenly distributed when repeatedly deformed. While *Particle Mechanical Constraint* uses cloth separators inside the device, our jamming tubes can be fitted with granular material inside several nylon mesh bags, which reduce inner movements. In case of filler material being based on layer jamming, such as paper and foam layers, there is no such problem as each layer has length similar to that of the entire tube. This advantage, as well as a better stiffness ratio between jammed and unjammed material (tested in Section 4.1.1) suggests that layers are preferable to granules for this kind of interfaces.

Tubes are larger than pads and can resist larger forces; they also constrain motion in a larger number of directions. However, as only one tube is attached to each finger, the device cannot independently constrain movement of individual joints of the finger so not all sensations can be reproduced.

Our design presented in Fig. 2 has tubes mounted on the inside of hand, in similar places as pneumatic cylinders in Rutgers Master II virtual system [3]. However, our proposal does not require pneumatic cylinders and additional hinges on fingers and palm. Multi degree of freedom joints of the RM II are replaced by the free movements of the elastic tube while the counteracting force generated by pneumatic cylinder is replaced by the stiffening of this tube.

Natural resilience of a rubber-like (latex or silicone rubber) material used for our jamming device returns the tube to its relaxed form with no need for additional actuation or a firm fixing to the user's hand.

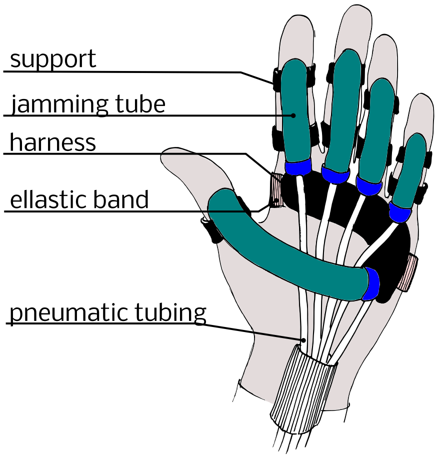


Fig. 2 Diagram of jamming tubes interface

3.3 Cutaneous Interface Through Vibration Motors

Jamming actuators used in our interface provide kinaesthetic feedback, through blocking human's joints. We propose adding a cutaneous haptic interface in the form of vibration motors placed on a user's fingertips. In our opinion these two sources of haptic sensations complement each other ideally.

Using vibrations as the only haptic feedback would be uncomfortable for the user in the scenario of grabbing and manipulating objects, because of two reasons: constant vibrations would be exhausting for the user, but using only short vibration to indicate the contact could lead to relaxing the grip after some time [6]. It is also impossible to transfer the feeling of hard surface being touched without using any pressure from the haptic device [10]. Vibration, however, greatly complements kinaesthetic and passive interfaces, as it can give a discrete event when a touch is detected, thereby informing users about the contact; enables displaying object's textures through modulating vibrations and has a much better dynamic range than jamming devices.

Vibration is realised through a pwm-controlled coin (shaftless, voice coil) vibration motors. Motors have a rated vibration speed of 12,500 rpm (208 Hz) and

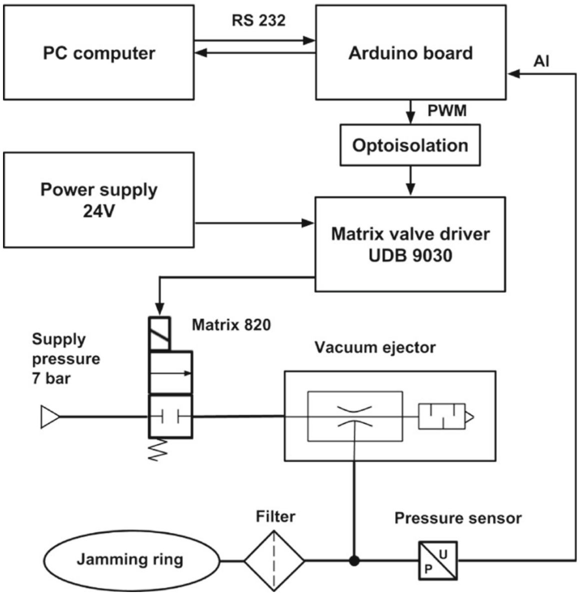


Fig. 3 Diagram of control system using vacuum ejectors for our jamming-based interface

can produce vibration with amplitude of 0.07 mm and force of 1.27 N. In current state, vibration is used to provide information about the event of grasping an object through brief vibration (0.2 s), but more sophisticated use (e.g. texture display) can be implemented.

3.4 Control

Controller for the jamming-based interface requires two circuits: electric and pneumatic, and has to be connected to other parts of teleoperation/ virtual environment system. We have tested a few concepts using different sources of vacuum: ejectors and micro-pumps. Our first control structure used in tests is shown in Fig. 3 with control program explained in Fig. 4. With this setup we can generate vacuums down to 0.2 bar (absolute) using pressures up to 7 bars supplying vacuum ejectors. This procedure requires fast pneumatic valves (Matrix 821 in our case) with specialised drivers being controlled by PWM signals; therefore, the controller is quite big and heavy, and also has to be connected to a pressure source with high air flow capability (min. 150 l/min).

The second structure employs vacuum micro-pumps and is shown in Fig. 5. This system can be powered from a simple Li-Pol battery with a voltage regulator. We have also used low-power ARM microcontroller MK20DX256 supported by ESP8266 chip providing Wi-Fi connection. Additional 3/2 pneumatic valve (from SMC) provides ventilation of the jamming tube to generate relaxing stage. It can also provide a trigger signal to start the jamming stage which was specifically tested in the following scenario: if a small vacuum reservoir is connected to the system (shown by dashed lines) some vacuum can be prepared before the jamming process has to be started and then begin the stiffening of the tube based on the trigger signal (correlated with the moment of gripping the object). We expected that a larger source of vacuum could speed up the jamming process but it turned out that the change in time constant was negligible – probably due to large pneumatic resistance in the jamming tube itself.

The second version of the control system is fully mobile when using battery power and Wi-Fi connection, as all the elements can be attached to the operator's arm (motors, valves, controller) or hand (jamming elements).

In our test system for teleoperation, controller receives commands from ROS-based teleoperation system using Wi-Fi/ UART and rosserial package (that provides a serialisation protocol with data integrity checks, multiplexing of multiple topics, and time synchronisation [2]). Teleoperation system is described

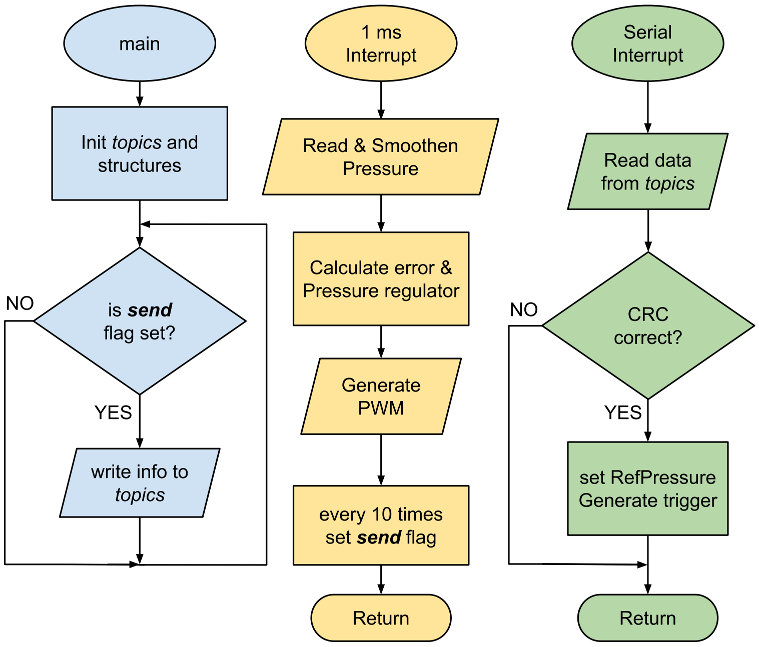


Fig. 4 General structure of the control program; the interrupt service routines are uninterruptible to secure data integrity

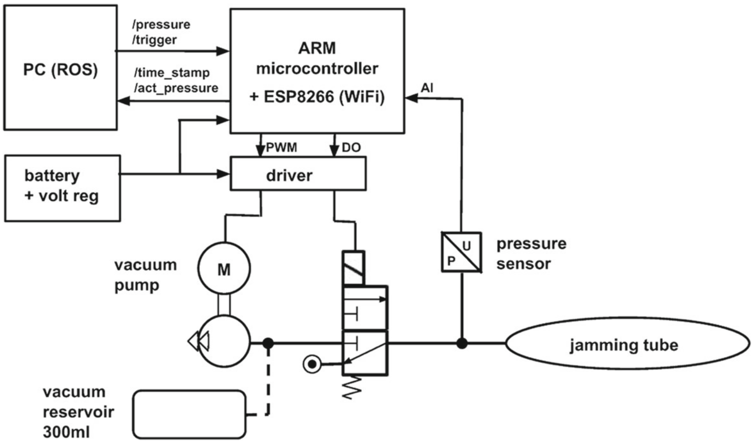


Fig. 5 Diagram of control system using vacuum micro-pumps for our jamming-based interface

in detail in Section 6 and controller for jamming elements appears as the "pneumatics driver" block in Fig. 15, trigger-based controller for vibration motors appears as "vibration driver".

Pressure in tubes and intensity of vibrations can be set through publishing to ROS topics; feedback information is also available in ROS. Two topics are used in both directions to communicate with haptic controller, they are: /pressure and /trigger to set the reference pressure and trigger signal, with /pressure being calculated by a higher level haptic controller to acquire some particular stiffness of the device, and /trigger being used to trigger the action of vibration motor. Feedback from the current state of the device is received through /time_stamp and /act_pressure topics. The control algorithm is realised by two interrupts to offer real-time behaviour: pressure measurement and filtration with 1 kHz, and asynchronous communication and triggering.

4 Experimental Evaluation

Several series of tests were conducted to measure static and dynamic behaviour of elements of haptic interface. As jamming phenomenon allows a change of stiffness; we were interested in: a range of this change for different materials (which should be preferably large to be able to simulate grasping a different material) and maximum value of stiffness. Also, we were interested in speed of change of stiffness as such property influences the perception of haptic system, or its transparency.

A further set of tests was conducted to understand how the rate of change of stiffness affects the dynamics of the interface. In the first one, a mass was dropped down when the jamming tube was being stiffened and in the second test the tube was stiffening when a finger was exerting pressure on it.

4.1 Methodology

4.1.1 Measuring the Static Change of Stiffness for Different Materials

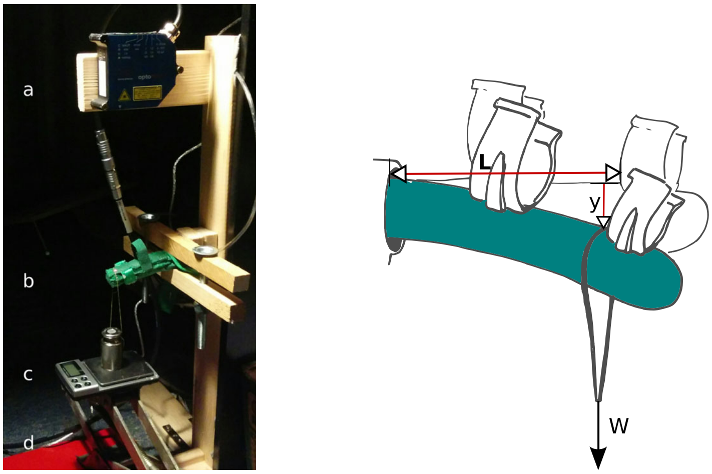
Using a technique similar to that of [14] we have measured the change of stiffness in a single tube from our interface. At the test stand shown in Fig. 6a a force was applied to the free end of the device and its deflection was measured (diagram shown in Fig. 6b). Changes in the vacuum pressure applied to the rubber chamber filled with the granular material or layers of material resulted in different intensity of the jamming and different deflections in the response to the same load.

The procedure was conducted for absolute pressure levels from 0.03 bar to 1 bar and four materials placed in the same latex membrane of a *jamming tube*: laser-cut wooden cubes (1.5 mm side), polystyrene beads (0.5 mm in diameter), 64 layers of 90 g paper with 3 layers of polyurethane foam, 112 layers of 90 g paper.

4.1.2 Measuring Dynamic Properties of the Tubes

Dynamic properties of tubes were measured using a fast (2.5 kHz) laser-based optical distance sensor

Fig. 6 **a** Test stand for measuring changes of stiffness. **a)** laser distance sensor **b)** measured specimen **c)** weight **d)** moving platform. **b** Diagram of the jamming tube as a cantilever



(a) Test stand for measuring changes of stiffness. **a)** laser distance sensor **b)** measured specimen **c)** weight **d)** moving platform

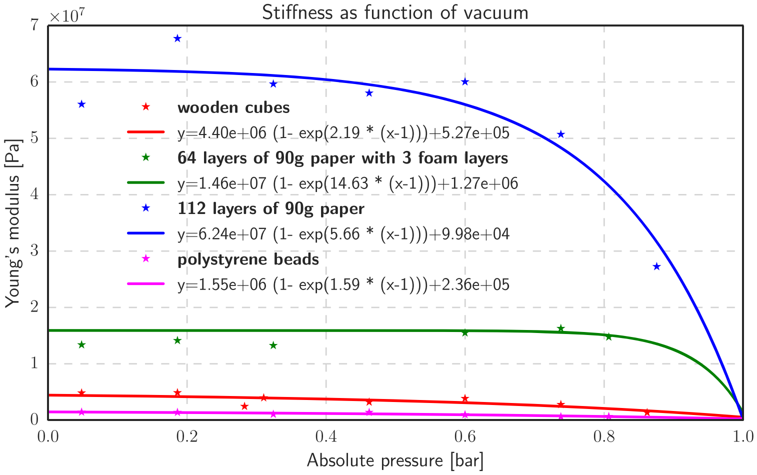
(b) Diagram of the jamming tube as a cantilever

(Fig. 6a) to record the position of the change of distance of a point on cantilever beam. Distance sensor was connected to data acquisition computer and could trigger other parts of the system, such as the jamming controler.

In the first of the experiments, the natural response of the tube being bent to a specific distance, then released to free vibration mode was measured. Pressure inside tubes was kept constant to a specific value that was changed between experiments, from 0.03 bar to 1 bar. Experiments were done with tubes being filled with laser-cut wooden cubes (around 1.5 mm side).

Further experiments were performed to understand the dynamics of transition between a relaxed form to stiffened form, when external forces have been acting. In this set of experiments, we were also interested in the feasibility of using a vacuum micropump as this could allow us to create a lightweight, possibly wearable device. Therefore jamming tube was used in setup shown in Fig. 5 with a closed loop system with a micropump used to control the pressure level. The

Fig. 7 Stiffness as a function of vacuum pressure for the jamming tube filled with various materials



system was used with a PID regulator for pressure control.

In the second experiment the jamming tube located in the test stand (Fig. 6a) was pulled down by the force 0.49 N generated by the mass dropped down. The moment the motion of the tube was detected by the laser distance sensor, the jamming procedure was automatically triggered. A motion of the jamming tube and the pressure inside the tube was registered for different reference pressures set to the local haptic controller.

In the third experiment, we wanted to check the behaviour of the jamming tube pressed by a human in a situation, similar to the normal operation, when a user's finger interacts with a tube when grasping a virtual object. A tactile sensor based on Takktile design [30] (with GY-68 chip used instead of MPL115A2) was used to measure pressure exerted by a human's finger on the jamming tube. Identically as in the previous experiment, immediately after the motion of the tube was detected by the laser distance sensor, the jamming procedure was started. The motion of the jamming tube, the pressure inside the tube, and the contact pressure between the finger and the tube was registered, for various reference pressures set to the local haptic controller.

4.2 Results

4.2.1 Measuring the Static Change of Stiffness for Different Materials

A deflection of a cantilever under the concentrated load at free end and measured at this point can be calculated using formula (1) [20, p. 262], [14].

$$y = \frac{WL^3}{3EI} \tag{1}$$

where: W is the concentrated load, I is the moment of inertia of the cross-section of the beam, L is the distance of the load from the support, E is the modulus of elasticity of the material.

Assuming a circular cross section with a diameter of 17 mm and a distance L measured as 65.6 mm, the Eq. 1 can be rewritten as Eq. 2:

$$W = E * y/22952.2 \tag{2}$$

where E is Young's modulus of the tested device – it can be estimated by fitting a linear function to the experimental data, for each vacuum pressure. As the equation is only true for small angles of deflection and only for linear elastic bending, Theil-Sen Regression was used for a robust estimation of Young modulus [25], through Scikit-Learn implementation [24].

An aggregate graph for stiffness as a function of vacuum pressure is presented in Fig. 7. Depending on filling material, changes of stiffness caused by growing vacuum can range from 6 times in the case of polystyrene beads to 40 times in that of the tube filled with 112 layers of paper. Maximum stiffness also varies, ranging from 0.002 GPa (comparable to silicone rubber) in the case of polystyrene beads to 0.07 GPa in that of multiple layers of paper (comparable to soft low-density polyethylene). It is also worth noting that stiffness did not significantly change for pressures lower than 0.4 bar.

Further studies of bead types and membrane couplings could give even better maximum stiffness, larger range of regulation and smaller hysteresis (as discussed in [14]).

4.2.2 Measuring Dynamic Properties of the Tubes

Natural responses of jamming tube for different materials Dynamic behaviour of a tube under certain pressure can be modelled as a damped spring with additional overdamped mode, which natural response can be described using Eq. 3.

$$y(t) = A_0 sin(\omega_d t + \phi) * exp(-\beta t) + B_0 exp(-\alpha t) + C \tag{3}$$

where: A_0 is an amplitude of damped oscillations, ω_d – a damped frequency of oscillations, ϕ – phase, β – damping coefficient, B_0 is an amplitude of additional mode, α – damping constant of additional mode, and C – an offset.

Meaning of additional mode B_0 is not yet understood but it is necessary in the model to have it converge. Such complex behaviour is typical for composite materials [18].

Additionally, natural frequency can be calculated using Eq. 4 and damping ratio using Eq. 5.

$$\omega_0 = \sqrt{\omega_d^2 + \beta^2} \tag{4}$$

$$\zeta = \frac{\beta}{\omega_0} \tag{5}$$

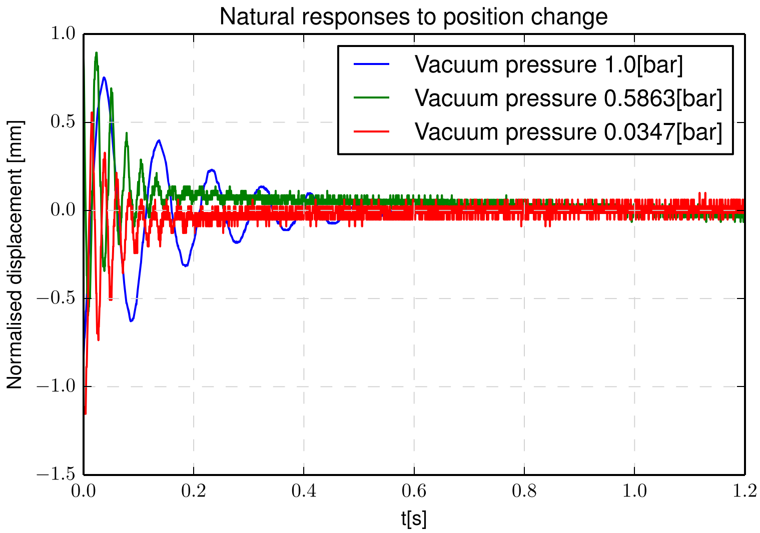


Fig. 8 Natural responses to position change of the jamming tube under different vacuum pressures

Natural responses, for different vacuum pressures are shown in Fig. 8. In case of a tube filled with wooden cubes, natural frequency changes from 55 rad/s for atmospheric pressure (1 bar) to 270 rad/s for vacuum (0.04 bar), as presented in Fig. 9.

As seen in Fig. 9, natural frequency of oscillations grows with the level of vacuum. However, damping ratio has a minimum for a pressure level of 0.44 bar.

Dynamic Response to Step Force Change The comparison of two cases: fully relaxed jamming tube and the reference pressure set to the value of 0.6 bar is shown in the Fig. 10.

Even though the jamming process is quite long (i.e. desired vacuum pressure is reached after 3 seconds) we can observe a significant change in the behaviour of the jamming tube immediately after jamming starts: oscillations are damped and the position is changing in an inertial manner.

Dynamic Response to Pressure Exerted by a Finger The comparison of two cases: fully relaxed jamming tube and the reference pressure set to the value of 0.4 bar is shown in the Fig. 11.

We can clearly see the restriction in the motion provided by the stiffening jamming tube – the green plot, of a reaction of a tube being stiffened, shows a smaller rate of distance change than the red one, when the vacuum pressure inside the tube began to change. We can also observe that the human can exert larger pressure on the stiff tube than on the relaxed one. Such behaviour gives the feeling of touching a harder object.

5 Prototype Devices

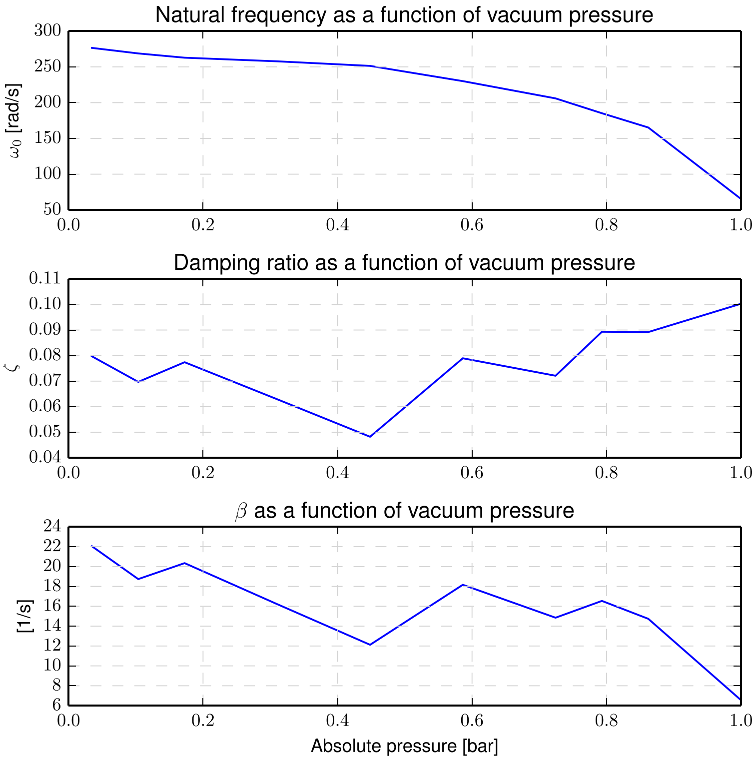
We have created a prototype haptic interface using jamming tubes to validate our design. Our prototype of jamming tubes, is shown in Fig. 12. In the current design, tubes are fixed to fingers and the hand palm through rubber harness. Additional grooves in each tube prevent the finger from slipping off the tube without restricting the movement parallel to the tube.

Tubes can be filled with different material, with layers of 90 g paper (> 100) giving the best absolute stiffness ability and jammed to unjammed stiffness ratio. Such design does indeed allow for blocking of the movement of fingers in the direction of the tubes, although the spreading movement of fingers is always constrained by the stiffness of paper itself in that direction.

Two part mould for tubes can be 3D printed or machined on a small CNC machine, and latex or a silicone rubber tube can be produced using rotocasting or brushing on rubber.

Through its simplified mechanical structure, the jamming haptic interface can be very lightweight, as a single tube with its harness weighs around 20 g (when filled with 100 layers of paper). Pneumatic motors used in tests weight 50 g each. With comparable number of degrees of freedom, CyberGrasp hand

Fig. 9 Natural frequency of oscillations, damping ratio ζ and damping coefficient β as a function of vacuum pressure



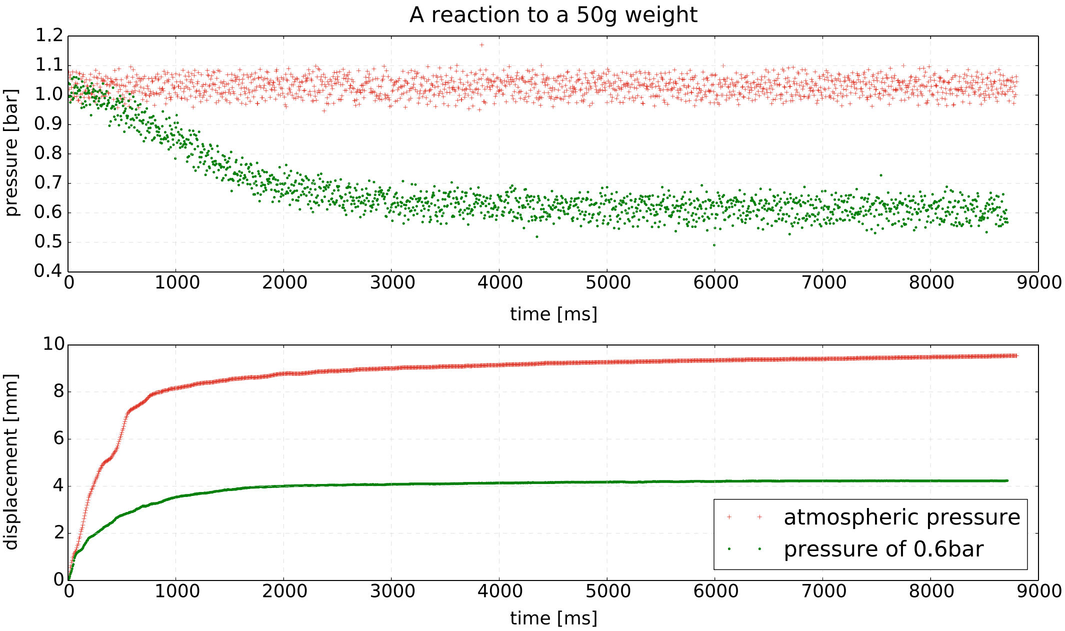


Fig. 10 Dynamic reaction of the jamming tube to the external force in case of fully relaxed tube (*red*) and stiffened (*green*)

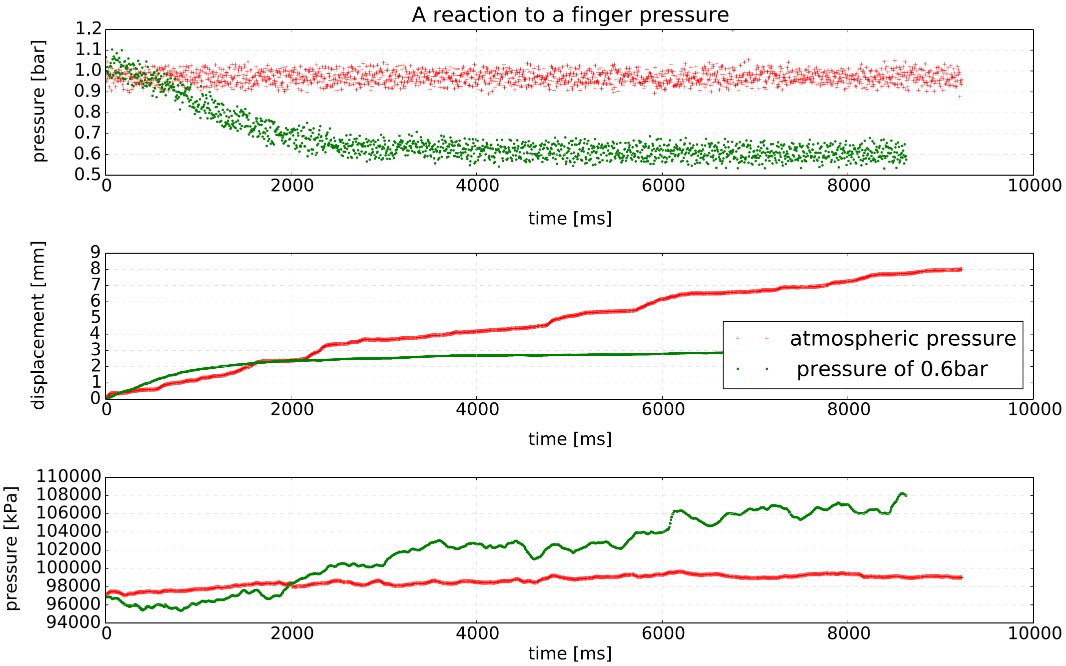


Fig. 11 Dynamic reaction of the jamming tube being pressed by a finger in case of fully relaxed tube (*red*) and stiffened (*green*). Filling material – layers of paper

exoskeleton, weighs 450 g, which gives 90 grams per finger [1]. The device is therefore 20 % lighter even when the motors are placed on user's arm. However, air tubes can also connect to stationary vacuum source.

In case of layers of paper used as filler material, our current design is able to resist forces of around 1 N with 2 mm displacement (on the fingertip) when a micro vacuum pump is used as vacuum source (0.57 bar) upto 7 N with 5 mm displacement when a stationary vacuum source generates 0.35 bar. This is slightly smaller than in a comparable commercial designs (CyberGrasp can resist forces of maximum 12 N).

While stiffened tubes have dynamics similar to a spring, the time constant for pressure (and therefore stiffness) change is quite high (equals around 0.5 s) and strongly depends on the structure and filler material of the tubes. When the vacuum is higher, the speed of air removal is reduced because air ducts inside the tubes become narrower; thus increases air

Fig. 12 Haptic glove prototype with jamming tubes on two fingers

Fig. 13 Prototype of jamming pads

friction. This necessitates that an additional haptic element with higher dynamics is needed – for our system we have proposed vibration motors placed at the fingertips.

The second prototype (Fig. 13) – the haptic interface with jamming pads, does constrain finger movements, but only in some directions. The wedge created when the device is jammed has also the tendency to slip, losing the ability to constrain particular joint. Also, the thumb has proven to be difficult to constrain with this simple design and requires further design effort.

6 Haptic Device Used as a Part of Teleoperation Interface

A practical application of our interface is an intuitive operation of a manipulator with a multi-finger, dexterous gripper in telemanipulation tasks. As explained in our previous paper [36], we focus on using robots in rescue/ exploration missions, where an operator can use his own hand to naturally control both a robotic arm and a gripper. To successfully control such a complex system, two sets of information are necessary (and have to be provided by the operator's actions): the operator's hand position and orientation is used to move the end-effector, while information about operator fingers' flexion is required to control fingers of dexterous gripper. Conversely, if the gripper can obtain any information about contact with an environment (e.g. through tactile sensors or gripper's joints moments) then this information can be conveyed back to the user through a haptic device via a mapping that is adequate to user scenario (considering such aspects as number of gripper's fingers and its degrees of freedom, specifics of information acquired from grippers sensors). A scheme of such a teleoperation system is presented in Fig. 14.

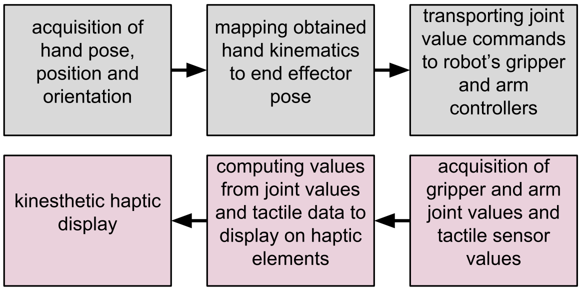


Fig. 14 Specification of a teleoperation system that uses an operator's hand pose as an input, and provides haptic feedback based on the grippers tactile sensors readings

We propose a teleoperation interface for a remote manipulation scenario based on a sensor glove with jamming-based haptic devices and integrated vision system (e.g. LeapMotion or Kinect). Data is collected and passed over through a ROS based control system – an environment which provides tools for data formatting, logging and transferring, as well as the framework connecting together in a flexible way, programs providing various functionalities.

The overall scheme of our interface is shown in Fig. 15. The main parts of the system are: (1) a glove-based interface which we are now extending with the haptic functionality, (2) integrated vision providing information about the absolute position of the user's hands and giving additional gestural control, (3) ROS nodes for data acquisition, grip recognition and trajectory generation, and (4) Schunk SDH controller giving access to the gripper's low level speed regulators and data readings from tactile matrices. In particular "haptic driver" provides necessary pneumatics and trigger values for the haptic system, based on tactile values from the gripper and mapping strategy used (such as setting the stiffness similar to that of grasped object or blocking some particular operator's fingers for some joint position etc.). Not shown on the diagram is a visualisation device which can be a computer screen or 3D glasses (e.g. Oculus Rift).

As noted in previous sections, jamming devices have limited dynamic range, therefore contact with an environment sensed through tactile sensors of the

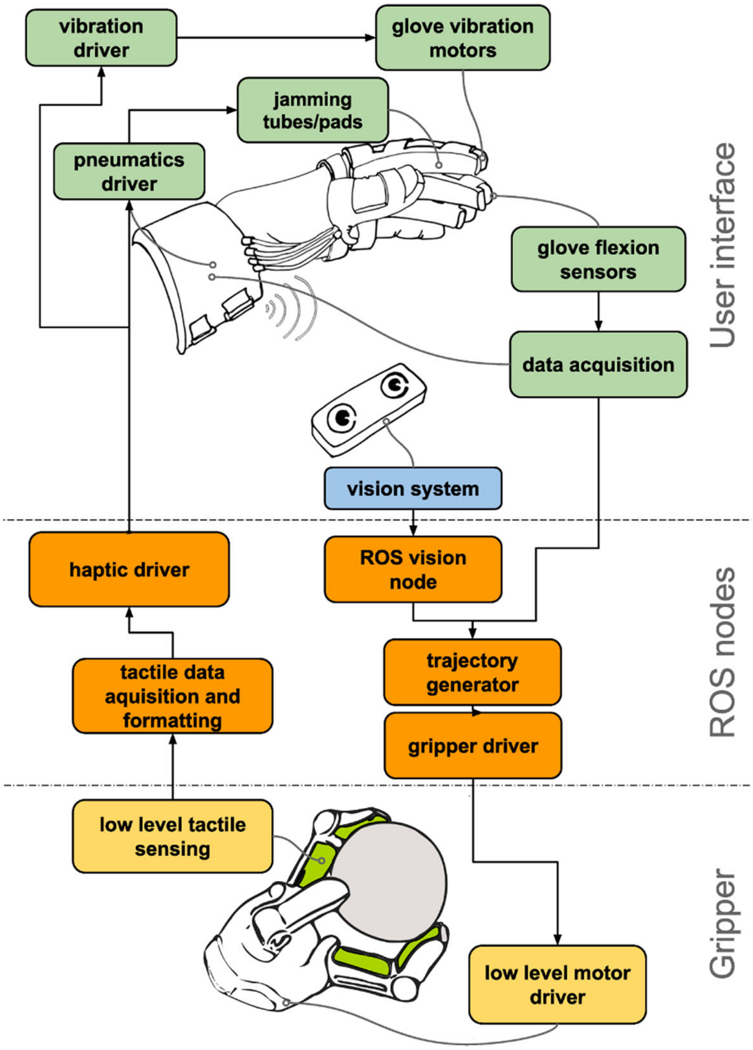


Fig. 15 Scheme of telemanipulation interface. *Green* – glove based interface, *blue* – vision system, *orange* – ROS nodes, *yellow* – Schunk SDH controller of the gripper

gripper is first transferred to a cutaneous interface to produce a prompt vibration signal. Then jamming interface stiffens to the level of sensed object's stiffness or some particular value preferred in a task being done.

The glove interface consists of:

1. Sensor glove with flexion sensors, providing information about the fingers' position – more details can be found in [34].
2. Vibration motors, placed on each finger; their vibration strength is controlled by a microcontroller, providing cutaneous haptic interface, described in Section 3.3.
3. Pneumatic jamming tubes or jamming pads with a vacuum control system, described in Sections 3.1 and 3.2, working as a kinaesthetic haptic device by blocking movements of the fingers.
4. A local controller for data acquisition and actuation, connected to the main computer via serial port or wireless network (Wi-Fi), described in Section 3.4.

7 Discussion and Conclusion

This work demonstrated how the jamming principle can be used to create a haptic glove interface for transferring sensation of grabbing and holding an object. An impression of grabbing a physical object improves ergonomy of long term tele-grasping because it reduces the strain on fingers as well as accuracy, and the operator's situation awareness.

Our jamming devices provided a way to simulate grasping an object through controllable stiffening of tubes or pads. By adding vibration motors and integrating haptic elements with sensor glove and vision system we have created a large and complete, yet still mechanically simple solution for remote grasping and manipulation.

We have presented two solutions: jamming tubes and jamming pads offering various behaviours and numbers of active degrees of freedom. We have investigated static and dynamic properties of tubes (being a main part of our proposed interface) filled with different jammable materials.

We have explained their characteristic features and limitations. At the current stage of our research, jamming tubes filled with layers of paper gave the best results (i.e. high maximum stiffness and large ratio of jammed to unjammed stiffness. The concept of jamming pads still requires further investigation as its movement blocking ability was limited.

Compared to several haptic displays presented in the previous review, our proposal based on jamming: had simpler construction but still could block multiple degrees of freedom of finger (in case of tubes not pads); was soft and light; was passive and safe, as it could not generate harmful forces, only restrain hand movement with set stiffness. It could not however project any active forces and could only influence reaction forces indirectly through changing stiffness. Also change of stiffness based on jamming takes considerable time (time constant around 0.5 s) and that translates in some movement still being possible when jamming is triggered – in our experiments, by using force of his finger user was able to displace the end of tube for a distance of 2 mm (around 2 % of the length) from the time jamming started. This can limit the use of the device as a way to precisely "feel" the object, especially when the hand is moving fast. However, when hand is moving slow enough to allow for full change of stiffness, device can inherently emulate grasping an object of particular stiffness.

Compared to other haptic devices using jamming phenomena (*Particle Mechanical Constraint* [19] and jammable exoskeleton placed on the back of hand described in[31]) placement of jamming elements on the palm of the hand provides sensation of grasping an object and does not block hand when opening it. Users cannot, however close their hand fully, even in the unjammed state, as jamming elements have some volume.

We have described the most recent version of our design, that allowed some operator mobility, because it was battery operated and had small, Wi-Fi enabled, control board, and mini vacuum pumps. Our design could be used as a part of teleoperation system for receiving kinaesthetic haptic feedback from a dexterous gripper. Other uses, such as part of a virtual reality system for simulation of grasping an object are also possible.

Our overall goal is to provide operators of mobile robots with a practical and economical interface that would enable intuitive gripping and manipulation. Therefore, our next goal is to test our augmented interface with its intended end-users.

Acknowledgments Authors would like to thank Honorata Lukasik, the author of the drawings in this article who also greatly helped with the construction of the prototypes; additionally, special thanks to Mikolaj Olejnik and Izabela Perenc, who helped with experiments and data acquisition.

References

1. CyberGrasp System v2.0, user guide (2009). http://www.upc.edu/sct/documents_equipament/d_184_id-485.pdf
2. Bouchier, P.: Embedded ros [ros topics]. IEEE Robot. Autom. Mag. **20**(2), 17–19 (2013)
3. Bouzit, M., Burdea, G., Popescu, G., Boian, R.: The rutgers master ii-new design force-feedback glove. IEEE/ASME Trans. Mechatronics **7**(2), 256–263 (2002)
4. Cates, M., Wittmer, J., Bouchaud, J.P., Claudin, P.: Jamming, force chains, and fragile matter. Phys. Rev. Lett. **81**(9), 1841 (1998)
5. Dipietro, L., Sabatini, A., Dario, P.: A survey of glove-based systems and their applications. IEEE Trans. Syst. Man Cybern. Part C Appl. Rev. **38**(4), 461–482 (2008). doi:10.1109/TSMCC.2008.923862
6. Edin, B.B., Howe, R., Westling, G., Cutkosky, M.: A physiological method for relaying frictional information to a human teleoperator. IEEE Trans. Syst. Man Cybern. **23**(2), 427–432 (1993)

7. Fabiani, L., Burdea, G., Langrana, N., Gomez, D.: Human interface using the rutgers master ii force feedback interface. In: Proceedings of the IEEE 1996 Virtual Reality Annual International Symposium, 1996, pp. 54–59 (1996). doi:10.1109/VRAIS.1996.490510
8. Follmer, S., Leithinger, D., Olwal, A., Cheng, N., Ishii, H.: Jamming User Interfaces: Programmable Particle Stiffness and Sensing for Malleable and Shape-Changing Devices. In: Proceedings of the 25Th Annual ACM Symposium on User Interface Software and Technology, pp. 519–528. ACM (2012)
9. Galiana, I., Ferre, M.: Multi-finger Haptic Interaction. Springer (2013)
10. Hale, K., Stanney, K.: Deriving haptic design guidelines from human physiological, psychophysical, and neurological foundations. IEEE Comput. Graph. Appl. **24**(2), 33–39 (2004). doi:10.1109/MCG.2004.1274059
11. Hale, K.S., Stanney, K.M.: Handbook of virtual environments: design, implementation, and applications, chap. 5, pp. 93–117. CRC Press (2002)
12. Hannaford, B., Wood, L., McAffee, D., Zak, H.: Performance evaluation of a six-axis generalized force-reflecting teleoperator. IEEE Trans. Syst. Man Cybern. **21**(3), 620–633 (1991). doi:10.1109/21.97455
13. In, H., Cho, K.J.: Exo-glove: A soft wearable robot for the hand with a soft tendon routing system. IEEE Robotics Automation Magazine (2014). Accepted
14. Jiang, A., Xynogalas, G., Dasgupta, P., Althoefer, K., Nanayakkara, T.: Design of a variable stiffness flexible manipulator with composite granular jamming and membrane coupling. In: 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 2922–2927 (2012). doi:10.1109/IROS.2012.6385696
15. Kim, Y.J., Cheng, S., Kim, S., Iagnemma, K.: A novel layer jamming mechanism with tunable stiffness capability for minimally invasive surgery. IEEE Trans. Reliab. **29**(4), 1031–1042 (2013)
16. Kortum, P.: HCI Beyond the GUI: Design for Haptic, Speech, Olfactory, and Other Nontraditional Interfaces, Chap. 2. Morgan Kaufmann Publishers Inc., San Francisco (2008)
17. Lawrence, D.A.: Stability and transparency in bilateral teleoperation. IEEE Trans. Robot. Autom. **9**(5), 624–637 (1993)
18. Luo, H., Hanagud, S.: Dynamics of delaminated beams. Int. J. Solids Struct. **37**(10), 1501–1519 (2000)
19. Mitsuda, T., Kuge, S., Wakabayashi, M., Kawamura, S.: Wearable Haptic Display by the Use of a Particle Mechanical Constraint. In: Proceedings of the 10Th Symposium On Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2002. HAPTICS 2002, pp. 153–158. IEEE (2002)
20. Oberg, E., Jones, F., Ryffel, H., McCauley, C., Heald, R.: Machinerys handbook 28th edition (2008)
21. Ou, J., Yao, L., Tauber, D., Ishii, H.: Methods and apparatus for layer jamming. US Patent App. 14/516,039 (2014)
22. Ou, J., Yao, L., Tauber, D., Steimle, J., Niiyama, R., Ishii, H.: Jamsheets: Thin interfaces with tunable stiffness enabled by layer jamming. In: Proceedings of the 8th Int. Conf, on Tangible, Embedded and Embodied Interaction, TEI '14, pp. 65–72. ACM, New York (2013). doi:10.1145/2540930.2540971
23. Sakaguchi, M., Furusho, J., Takesue, N.: Passive force display using er brakes and its control experiments. In: Proceedings of the IEEE Virtual Reality, 2001, pp. 7–12 (2001). doi:10.1109/VR.2001.913764
24. Scikit-learn.org: Theil-sen regression scikit-learn 0.17 documentation. http://scikit-learn.org/stable/auto_examples/linear_model/plot_theilsen.html (2015)
25. Sen, P.K.: Estimates of the regression coefficient based on kendall's tau. J. Am. Stat. Assoc. **63**(324), 1379–1389 (1968)
26. Simon, T.M., Smith, R.T., Thomas, B.H.: Wearable jamming mitten for virtual environment haptics. In: Proceedings of the 2014 ACM International Symposium on Wearable Computers, ISWC '14, pp. 67–70. ACM, New York (2014). doi:10.1145/2634317.2634342
27. Spirkovska, L.: Summary of tactile user interfaces techniques and systems (2004)
28. Stanley, A., Gwilliam, J., Okamura, A.: Haptic jamming: A deformable geometry, variable stiffness tactile display using pneumatics and particle jamming. In: World Haptics Conference (WHC), 2013, pp. 25–30 (2013). doi:10.1109/WHC.2013.6548379
29. Steltz, E., Mozeika, A., Rembisz, J., Corson, N., Jaeger, H.: Jamming as an Enabling Technology for Soft Robotics. In: SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring, pp. 764,225–764,225. International Society for Optics and Photonics (2010)
30. Tenzer, Y., Jentoft, L.P., Howe, R.D.: The feel of mems barometers: inexpensive and easily customized tactile array sensors. IEEE Robot. Autom. Mag. **21**(3), 89–95 (2014)
31. Thompson-Bean, E., Steiner, O., McDaid, A.: A Soft Robotic Exoskeleton Utilizing Granular Jamming. In: 2015 IEEE International Conference On Advanced Intelligent Mechatronics (AIM), pp. 165–170. IEEE (2015)
32. Visell, Y., Duraikkannan, K.A., Hayward, V.: A Device and Method for Multimodal Haptic Rendering of Volumetric Stiffness. In: Eurohaptics (1)'14, pp. 478–486 (2014)
33. Yokokohji, Y., Muramori, N., Sato, Y., Kikura, T., Yoshikawa, T.: Design and path planning of an encountered-type haptic display for multiple fingertip contacts based on the observation of human grasping behavior. In: Proceedings of the ICRA '04. 2004 IEEE Int.l Conf. on Robotics and Automation, 2004, vol. 2, pp. 1986–1991 (2004). doi:10.1109/ROBOT.2004.1308115
34. Zubrycki, I., Granosik, G.: Test setup for multi-finger gripper control based on robot operating system (ros). In: Proceedings of 9th Int. Workshop on Robot Motion and Control, pp. 135–140 (2013). doi:10.1109/RoMoCo.2013.6614598
35. Zubrycki, I., Granosik, G.: Using Integrated Vision Systems: Three Gears and Leap Motion, to Control a 3-Finger Dexterous Gripper. In: Recent Advances in Automation, Robotics and Measuring Techniques, pp. 553–564. Springer (2014)
36. Zubrycki, I., Granosik, G.: Intuitive user interfaces for mobile manipulation tasks. Journal of Automation Mobile Robotics & Intelligent Systems **8**(1) (2015)

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