2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

A novel actuation technology for safe physical human-robot interactions

Laure Esteveny, Laurent Barbé, Bernard Bayle
ICube, Strasbourg University-CNRS, France
Email: {lesteveny, laurent.barbe, bernard.bayle}@unistra.fr

Abstract— **The design of intrinsically safe systems is an important issue in the development of physical human-robot interactions, in particular in the medical field. In this paper, we explore a new approach, motivated by a medical robotic application framework. The system is statically balanced, in any configuration. Its actuation results from a controllable modification of the balancing. This notably limits the interaction forces between the robot and its environment, but yet authorizes important features like accurate positioning or tracking while in contact, which are key characteristics for the application. In this paper, the robotic device principle is introduced, together with its original actuation, which is developed and experimentally assessed for a one DOF system. Capabilities such as trajectory tracking in the free space, reaction to unexpected collision and tracking of a moving environment are reported. The generalization to more DOF, as required to complete medical tasks, is also discussed.**

I. Introduction

A. Background

Robotic manipulation devices interacting with users have been considerably developing over the last two decades, in order to help human operators perform complex tasks, carry heavy loads, or improve their accuracy [1], [2]. Innovative design methods have therefore been proposed to guarantee users safety during such physical human-robot interactions [3]–[5]. This problem is of course fundamental in medical applications, where the protection of the patients and the staff is a top priority concern [6].

To give a concrete illustration to the reader, we will take the example of robotic assistance for percutaneous procedures in interventional radiology [7], [8]. These image-guided procedures consist in the positioning of needles or needle shaped tools for diagnostic or therapeutic purpose. Robotic assistance, which allows for instance automatic registration, improved accuracy or remote manipulation, is a very interesting opportunity to further develop these medical techniques. However, the robotic design has to comply with highly demanding constraints, specially in terms of safety. While most of the earlier systems were based on robots attached to the operation table [9], [10], it is now well known that in this case the robot has to compensate for the patient's physiological motions [11], or the needle has to be released when not inserted, in order to limit tissue laceration or involuntary needle penetration. Additionally, these robots, generally quite rigid, have a large workspace and collisions (with the imaging device, with the staff) have to be taken into account. Whereas patient-mounted systems [12] offer an interesting solution for partial motion compensation, they also suffer from drawbacks like e.g. limited workspace, base attachment compliance, and difficult access to the needle because of their compactness.

The aforementioned requirements are quite general when considering soft tissues interactions. Medical robotic devices have to be safe for the medical staff who can possibly interact with them but also to be safe with the patient. So far, these safety issues have not always been considered as a basic requirement but often as a demanding specification, limiting the device performances. Paradoxically, recent man-robot safety improvements have not yet been applied to design of medical devices, may be because they had been developed with a more general objective of safe physical human-robot interaction [2]. Two main methods are reported in the literature in order to obtain intrinsically safe physical human-robot interactions. The first one is focused on actuation, and consists in controlling the joints stiffness or damping by means of compliant actuators [4], [5]. Typically, an actuator is used to control the joint position whereas a second one is used to control the joint stiffness or damping, according to safety or accuracy concerns. Nevertheless, this approach leads to power-consuming systems and require complex control strategies, mainly due to the use of several actuators per joint. In order to limit the number of actuators, a second method consists in the design of intrinsically safe mechanisms [13], [14]. These systems are built with parts having low masses and inertia, and their actuation torque is mechanically limited. The main advantage of such systems is that they give much more intrinsic guarantees than conventional robots, whose safety mainly relies on interaction control.

B. Purpose and contributions

An innovative actuation strategy focused on safety concerns, which combines intrinsically safe design and indirect actuation, is developed in this paper, and assessed experimentally using a one degree of freedom (DOF) prototype. This system is statically balanced to passively compensate for the gravitational effects, thus limiting the influence of the device mass and inertia during interactions. This also limits actuation power, and then increases intrinsic system safety. The originality of the proposed solution relies on the design of the mechanism that indirectly actuates the system by modifying its balancing so as to follow a planned trajectory or to remain in contact with a moving environment, without developing large forces.

Though realistic medical positioning tasks require at least

3 DOF, we first present and evaluate this actuation using an elementary mechanism (a revolute joint with a bar). The proposed mechanism is presented in section II. It has been initially studied from a theoretical point of view and simulated in [15]. The contributions of the present paper are the prototyping, control and experimental evaluation of the solution. In particular, the actuator efficiency is experimentally assessed in section III, before giving perspectives for the generalization of the actuation system to multiple DOF in section IV.

II. General principle

A. Proposed solutions

We first mechanically compensate the device for gravity. Without the influence of gravity, only the inertia and the friction effects have to be counteracted to move the system. As a consequence, the required actuation torque can be low. The statically balanced system will remain stable in any configuration, even without friction or braking. This is a classical problem and the balancing is generally performed by means of counterweights [16] or springs [17]. Counterweight balancing solutions are easy to carry out. However, they often result in heavy and cumbersome systems. Springs offer an interesting alternative to obtain lighter systems [17] even if they lead to more complex mechanisms.

The proposed solution consists in balancing the system by means of springs, preferred to counterweights to limit the embedded mass and the inertia and then, in indirectly actuating the system by locally changing the balancing around the system equilibrium.

Choosing an indirect actuation is interesting because the actuation torque can be limited mechanically which is preferred to direct actuation, which would require software limitations.

This actuation approach is somehow similar to the one used in ball-shaped robots [18], where moveable masses are displaced so as to modify the gravity center of the robots. A comparable approach is also proposed for pick and place robots in [19], where variable payloads can be balanced by controlling the counterweights positions or masses depending on the payload.

The actuation approach proposed hereafter consists in creating a driving torque by moving the attachment points of the static balancing mechanism. This principle is so far used without any actuator to adjust the balancing of systems with variable payloads [20], [21]. In this paper, we propose to actively control the spring deflection in order to create the driving torque.

B. Actuation description

We now focus on the proposed indirect actuation system principle. Such an actuation allows us to mechanically limit the joint torque, whatever the actuator torque. It is a major safety advantage, compared to systems where actuators are directly put on the joint. Furthermore, the joint remains backdrivable even if the actuator is not.

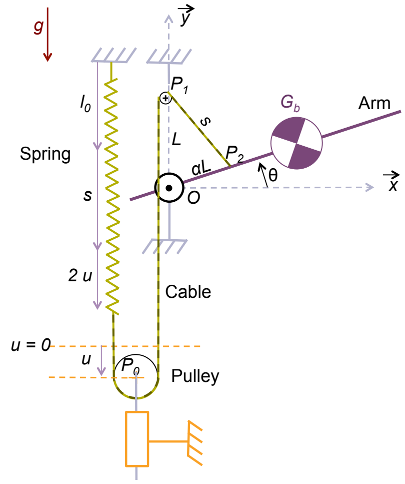

Fig. 1. Mechanism principle

The functional principle of the proposed mechanism is illustrated in Fig. 1 by a 1 DOF system, originally introduced in [15]. To allow a better understanding, the proportions are not respected and all parts are drawn in a same plan.

The mechanism is composed of three main parts: the arm, the balancing system and the actuation system. The arm is a rigid bar of mass m_b. Its center of gravity is denoted by G_b, with $\|\overrightarrow{OG_b}\| = l_{gb}$ where O is the center of rotation of the joint. The inertia of the arm, expressed at G_b along $\vec{z}$, is I_b. The angular position is given by the angle θ. The balancing system uses a linear spring which is attached to the arm by means of a non-extensible cable. At one end, the cable is attached to the arm in P_2, and at the other end, it is attached to the spring. To obtain a perfect balancing, the cable passes through a fixed point P_1 located along the $\vec{y}$-axis, and the distance s between P_1 and P_2 should be equal to the spring deflection. Note that s depends on θ. Then, the cable passes by a pulley centered on P_0. The elongation of the spring can be modified by the indirect actuation system, which results from a linear motion u of P_0 along the $\vec{y}$-axis. The U-turn around the pulley makes the mechanism more compact and minimizes the actuator stroke length.

The arm is subjected to three external torques resulting from gravitational effects Q_{pes}, balancing and actuation Q_{el}, and interaction with the environment Q_{ext}. Assuming that friction is negligible and that the mass and inertia of the pulley and the spring are negligible compared to the mass and inertia of the arm, the equation of motion of the overall system can be written as:

$$(I_b + m_b l_{gb}^2)\ddot{\theta} = Q_{ext} - Q_{el} - Q_{pes} \tag{1}$$

with

$$Q_{pes} = m_b l_{gb} g \cos\theta \tag{2}$$

$$Q_{el} = -kL^2\alpha\cos\theta - \frac{2\alpha k L\cos\theta}{\sqrt{1+\alpha^2-2\alpha\sin\theta}}u \tag{3}$$

where k is the stiffness of the spring and g the acceleration of gravity constant. Lengths L and αL, with $\alpha > 0$, are the distances between O and, respectively, P_1 and P_2.

According to equations (2) and (3), and considering $Q_{ext} = 0$, the static balancing is achieved when the two following conditions are met:

$$u = 0 \text{ and } k = \frac{m_b l_{gb} g}{L^2 \alpha}$$

When k is substituting into (1), the equation of motion is then written as:

$$(I_b + m_b l_{gb}^2)\ddot{\theta} = Q_{ext} + \tau \tag{4}$$

with τ the driving torque:

$$\tau = \frac{2 m_b l_{gb} g \cos\theta}{L\sqrt{1 + \alpha^2 - 2\alpha \sin\theta}}\, u \tag{5}$$

Note that τ is defined as the indirect actuation torque available at the joint, which is different from the motor torque.

Such an actuation principle can only be used with systems which are affected by gravity. A second requirement is about the spring tension, which needs to remain positive. In this way, obtaining a bilateral actuation is only possible if the spring is pre-tensioned, i.e. $\alpha \neq 1$. The actuator range directly depends on the spring pre-tension, which is $s_{(\theta=\pi/2)} = L(1-\alpha)$ when $\theta = \pi/2$. The minimal displacement u_{min} is then calculated to maintain the spring tensioned for any configuration: $u_{min} = -L(1-\alpha)/2 < 0$. To ensure the symmetry of the provided torque, the maximal displacement is $u_{max} = -u_{min} > 0$. It has to be compatible with the maximal acceptable spring deflection, which should be longer than $s_{(\theta=-\pi/2)} + u_{max}$.

Note that the system can not be actuated when $\theta = \pm\pi/2$ since in this case $Q_{el} + Q_{pes} = 0, \forall u$. In the remainder of the text, θ will vary in $]-\pi/2;\pi/2[$ to avoid these singularities. It can also be highlighted that the indirect actuation system cannot produce higher driving torque than the torque resulting from gravity without balancing. However, only low torques are needed to perform movements thanks to the arm static balancing. As a result, this torque limitation is not an issue. At the contrary, it brings an additional working safety.

C. 1-DOF Prototype

The 1 DOF system prototype is presented in Fig. 2. A 400 mm long bar with a mass of 81 g has been chosen with a size and a mass compatible with the human capabilities. The arm gravity center is l_{gb} = 140 mm away from the joint axis. The design methodology presented in [15] allows us to select a standard spring with a stiffness of k = 0.2 N·mm^{-1}, a maximal deflection of 100 mm and an initial preload of 2 N. Then we choose OP_1 = 33 mm to have a compact joint and to guarantee that the maximal spring deflection is admissible, which leads to OP_2 = 17 mm [15]. The maximal force required to translate the pulley is then less than 35 N.

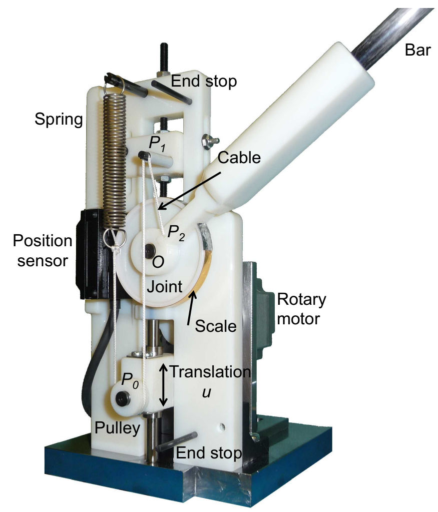

Fig. 2. Built prototype.

The arm is built from a 10-mm diameter carbon fiber bar, a material known to be light and very rigid. The system parts are manufactured by polymer rapid prototyping. Compared to materials commonly used in robotics, these materials reduce drastically the mass and inertia. Two end stops are fixed to the base frame to limit the device workspace to $]-1.3; 1.3[$ rad. The spring is a standard component fixed to a polyethylene cable made of Dyneema, particularly interesting for its high stiffness, which is compatible with the hypothesis of a non-extensible cable. To limit the friction along the cable path, pulley and axes with ball bearings are used in O, P_0 and P_1. The diameter of the axis passing through P_1 should be as small as possible to meet the balancing conditions. With a 2 mm diameter, it introduces a torque error lower than 3 N·mm. This error is maximal at the workspace boundary but its influence is not perceptible as it is even lower than friction effects.

The arm position is measured by a non-contact optical position sensor Renishaw RGS40, placed in front of a scale sticked on the external diameter of the joint. This choice limits added inertia to the arm. The obtained resolution is less than 0.1 deg. The translation u is performed by means of a slider-crank mechanism, not visible in Fig. 2, connected to an Harmonic Drive rotary motor (FHA-8C series) with an optical encoder of resolution 10^{-3} deg. Other actuator solutions exist but this choice have several advantages such as:

- the mechanical limitation of u, which bounds the driving torque and then the effort that the arm can apply. Furthermore, it makes it possible to protect the device itself by limiting the extension of the springs ;
- higher dynamic performances can be achieved by a

rotary motor compared to linear ballscrew for instance ;
- by properly chosen the dimensions of the crank and the connecting rod, the system can be very compact ;
- even if the behavior of such a system is non-linear, it is quite easy to control with the arm position sensor in addition to the motor sensor.

The motor and the transmission are located in a plane parallel to the base frame, in order to limit the system bulk. The crank and the connecting rod are respectively 17 and 37 mm long. With this slider-crank system, according to the workspace dimensions, u can vary from -16 to 16 mm in the linear domain of the spring. This represents an half-rotation of the motor.

III. Control and experimentations

This section introduces the mechanism control strategy and its implementation. The goal is to follow a preplanned trajectory in a free environment or in contact with a moving environment, possibly with human interactions.

A. Control strategy

In order to guarantee the desired motor torque and to reject the external forces, such as the reaction force of the spring, an inner position control loop has been implemented. The controller has been designed in such a way that the feedback is under-damped, and with a settling time of 40 ms. Then, an outer position loop has been designed to control the position θ of the joint. According to equation (5) the driving torque depends on the current position of the arm. As a consequence, the position controller has been chosen in order to take into account this dependency. The proposed control law for the outer position loop can be written as:

$$u = K_p(\theta)(\theta^* - \theta) - K_d(\theta)\dot{\theta} \qquad (6)$$

where θ^* is the position reference and $K_p(\theta)$ and $K_d(\theta)$ are the gains of the controller, which are adapted over the workspace:

$$K_p(\theta) = w_n^2 C(\theta) \quad \text{and} \quad K_d(\theta) = 2\zeta w_n C(\theta) \qquad (7)$$

with:

$$C(\theta) = \frac{(I_b + m_b l_{gb}^2) L\sqrt{1 + \alpha^2 - 2\alpha \sin\theta}}{2 m_b l_{gb} g \cos\theta} \qquad (8)$$

where w_n and ζ are respectively the desired natural frequency and damping ratio.
Under the assumption that no friction affects the system and that there is no interaction with an environment, the closed-loop model can be written as the second-order differential equation: $\ddot{\theta} + 2\zeta w_n \dot{\theta} + w_n^2 \theta = w_n^2 \theta^*$. The trajectory tracking properties are ensured by properly choosing w_n and ζ. The system is stable over the whole workspace. This control strategy was only validated in [15] with simulations. In the next section the experimental assessment of the device allows to emphasize the effects of the prototype design and the influence of the unmodeled effects.

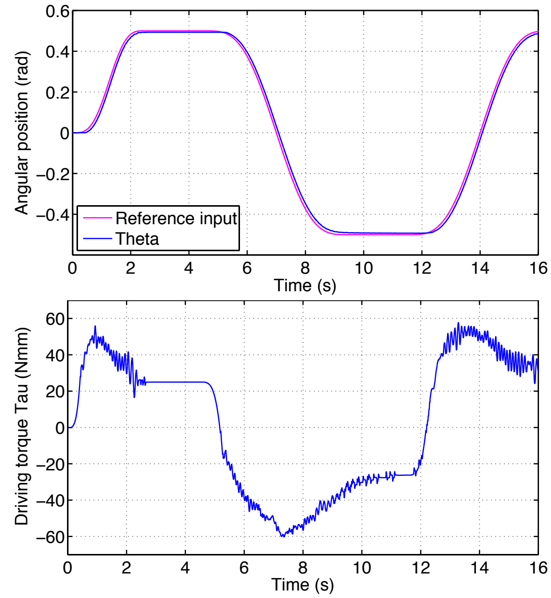

Fig. 3. Trajectory tracking. Top: Specified and performed trajectories. Bottom: Driving torque τ.

B. Experimental results and discussion

All experiments have been carried out with the same controller tuned with w_n = 30 rad·s^{-1} and ζ = 0.7 and computed with the dynamic parameters from CAD model (eq. (8)). A spring is mounted on a rigid platform equipped with a force sensor to serve as soft environment. The force sensor is only used to evaluate the forces when the arm comes into contact with the environment.

1) Trajectory following: The position trajectory reference and measured position of the arm are plotted in Fig. 3, top. It can be observed that the position control loop remains stable all along the trajectory. The mean absolute tracking error remains under 0.02 rad.

According to the equation (5) and to the measurement of the actuator position, the driving torque τ is calculated and represented in Fig. 3, bottom. It is important to notice that the driving torque symmetry relative to the arm position is possible because of gravity compensation. However, this symmetry is not perfect in practice, especially at low velocity because of the friction on the pulleys. As illustrated in Fig. 3 (bottom), the driving torque remains at $\pm$25 N·mm during the stationary phases when the friction effect on the mechanism is more important.

2) Collision with a static environment: The second experiment illustrates the behavior of the mechanism during an unexpected collision with a static environment, as it can appear with the medical staff for instance. The arm follows the same trajectory as in the previous experiment, but there is a collision with an environment characterized by a stiffness of 0.176 N·mm^{-1}, positioned at -0.068 rad from the origin (Fig. 4, top). When the collision with the environment occurs, some oscillations around the equilibrium position can be observed, but the arm always remains in contact with the environment and the force remains lower than

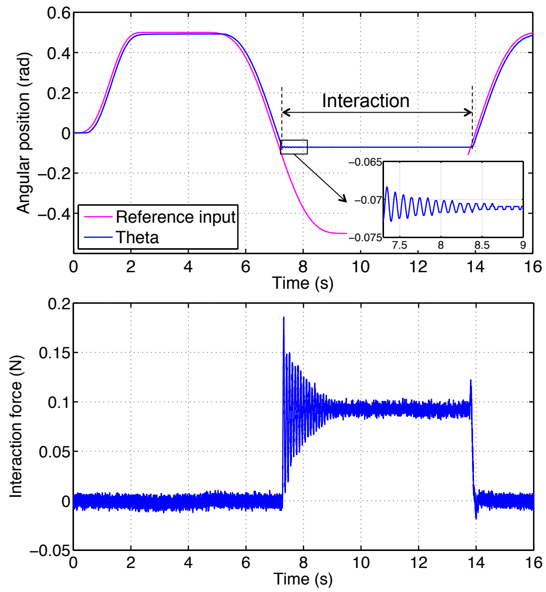

Fig. 4. Collision with a static environment. Top: Specified and performed trajectories. Bottom: Interaction force.

0.2 N (Fig. 4, bottom). After the oscillations, the arm is stable at the equilibrium position. According to the safety capabilities of the developed actuation, the force applied by the arm on the environment reaches its maximum value of approximately 0.1 N.

3) Interaction with a moving environment: This working mode allows the device to follow a moving environment without applying large forces. The same control strategy is used but in this case, the reference input is a static position, chosen inside the environment at -0.03 rad. The environment, in contact with the robot at the arm tip, follows a sinusoidal motion of amplitude 4 mm (which is in the order of respiratory motion amplitude). Figure 5, top, shows the trajectories specified and performed by the mechanism.

During the first two seconds of the experiment the end-effector of the arm reaches the surface of the environment. Then, the mechanism follows the sinusoidal motions and remains in contact with the surface of the environment by applying a small positive force (Fig. 5, center). The force applied on the environment can easily be modified by changing the reference input of the position control loop.

IV. Generalization to more DOF

In the previous section, the results obtained with the 1-DOF experimental testbed suggest that the indirect actuation principle is efficient and ensures safe physical human-robot interactions. These promising results encouraged us to develop a 3-DOF robot dedicated to 3D positioning tasks. The prototype of the device is presented in Fig. 6. The objectives of the design are: integrating the indirect actuation, adapting the size of the robot to the manipulation capabilities of the human and increasing the transparency for comanipulation. The robot is based on a parallelogram structure which allows

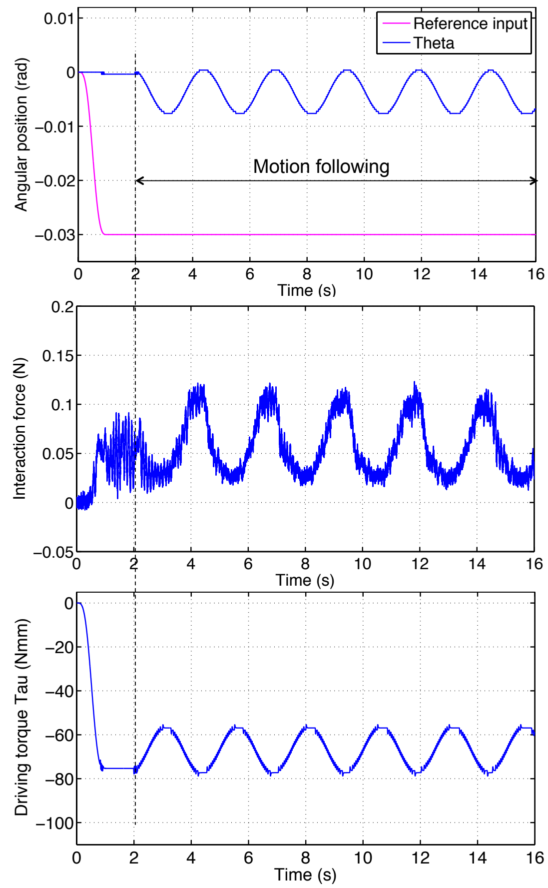

Fig. 5. Moving environment following. Top: Performed trajectory. Center: Interaction force. Bottom: Driving torque.

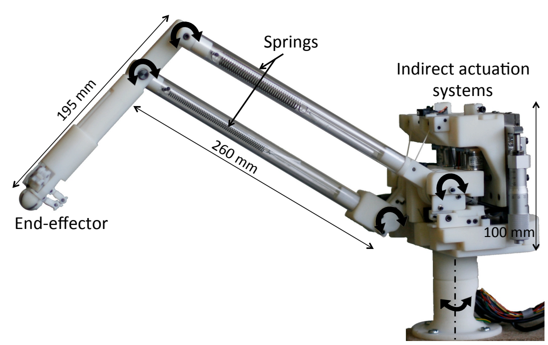

Fig. 6. 3-DOF prototype.

an easier integration of the static balancing system, with the actuators at the base of the robot and making a stiffer structure. As the vertical rotation of the robot is not subject to gravity, it is actuated by a simple motor with a capstan, while the other two directions use the indirect actuation principle previously presented.

The system compactness has been preserved by integrating the springs used for static balancing inside the robot links. In order to increase its transparency, the robot has been lightened by using polymers for most of the parts. Furthermore, systems with pulleys have been preferred to slider-crank mechanisms for compactness and friction limitation.

The prototype of the 3-DOF robot for the positioning tasks has been built and the first experiments of gravity compensation have been carried out successfully (see attached video). The development of the 3-DOF system for the medical application of needle insertion is still under process and is far beyond the scope of the present paper. However, it is interesting for the reader to know that multiple DOF extension is possible as it gives more generality to the concept presented in the previous section. Note that the size and mass of the considered device are compatibles with human manipulation capabilities. However, the same principle can be easily extended to large and heavy systems. In this case, the spring stiffness is increased and more power is required to modulate the extension of the springs. To keep small actuators and then compact systems, dedicated force demultiplying mechanisms can be added.

V. Conclusions and perspectives

This paper presents a new actuation technology for safe physical human-robot interactions. It consists in the indirect actuation of the robotic device by the control of its balancing system. Such an actuation has many advantages for the safety of the interaction, most notably the mechanical limitation of the joint torque and the joint backdrivability. This system is also interesting because the actuator can easily be put away from the joint, typically at the base.

The system static balancing is achieved classically by means of springs. Then, the major originality comes from the actuation resulting from the modification of the spring deflection around the equilibrium configuration. This concept is illustrated with a one DOF prototype, implemented and experimentally used to prove the feasibility of the proposed approach. To perform these experiments, an adaptive control law has been implemented. The obtained results are satisfactory in terms of safety and accuracy and therefore validate the detailed principle. The approach has been generalized to a 3-DOF prototype which takes into account several design improvements, in particular on friction minimization and compactness enhancement. Even though not developed in the present paper, this system is very promising because of its lightness, its compactness and its backdrivability, which makes it a perfect device for haptic manipulations or fine interactions.

Future works will focus on the development of the 3-DOF system control and its implementation and adaptation for medical tasks.

Acknowledgment

The authors wish to thank V. Van Geirt for his help in the development and CAD model of the 3-DOF prototype.

This work has been supported by the Alsace Regional Council, by the *Institut de chirurgie mini-invasive guidée par l'image* (IHU Strasbourg) and by the French government (ANR-10-EQPX-44 and ANR-11-LABX-0004).

References

[1] J. E. Colgate, M. Peshkin, and W. Wannasuphoprasit, "Cobots: Robots for collaboration with human operators," in *International Mechanical Engineering Congress and Exhibition*, vol. 58, Atlanta, 1996, pp. 433–439.

[2] R. Alami, A. Albu-Schaeffer, A. Bicchi, R. Bischoff, R. Chatila, A. De Luca, A. De Santis, G. Giralt, J. Guiochet, G. Hirzinger, F. Ingrand, V. Lippiello, R. Mattone, D. Powell, S. Sen, B. Siciliano, G. Tonietti, and L. Villani, "Safe and dependable physical human-robot interaction in anthropic domains: State of the art and challenges," in *IEEE/RSJ International Conference on Intelligent Robots and Systems, Workshop on Physical Human-Robot Interaction*, Beijing, 2006.

[3] A. Bicchi, M. Peshkin, and J. Colgate, "Safety for physical human–robot interaction," in *Springer Handbook of Robotics*, B. Siciliano and O. Khatib, Eds. Springer Berlin Heidelberg, 2008, pp. 1335–1348.

[4] R. Van Ham, T. Sugar, B. Vanderborght, K. Hollander, and D. Lefeber, "Compliant actuator designs. Review of actuators with passive adjustable compliance/controllable stiffness for robotic applications," *IEEE Robotics Automation Magazine*, vol. 16, no. 3, pp. 81–94, 2009.

[5] B. Vanderborght, A. Albu-Schaeffer, A. Bicchi, E. Burdet, D. Caldwell, R. Carloni, M. Catalano, O. Eiberger, W. Friedl, G. Ganesh, M. Garabini, M. Grebenstein, G. Grioli, S. Haddadin, H. Hoppner, A. Jafari, M. Laffranchi, D. Lefeber, F. Petit, S. Stramigioli, N. Tsagarakis, M. Van Damme, R. Van Ham, L. Visser, and S. Wolf, "Variable impedance actuators: A review," *Robotics and Autonomous Systems*, 2013.

[6] J. Troccaz, Ed., *Medical robotics*. Wiley and ISTE, 2012.

[7] K. Cleary, A. Melzer, V. Watson, G. Kronreif, and D. Stoianovici, "Interventional robotic systems: Applications and technology state-of-the-art," *Minimally Invasive Therapy*, vol. 15, no. 2, pp. 101 – 113, 2006.

[8] B. Bayle, O. Piccin, L. Barbé, P. Renaud, and M. de Mathelin, *Robot-Assisted Procedures in Interventional Radiology (chapter 11)*. Springer, 2010, pp. 191–205.

[9] D. Stoianovici, "Urobotics - Urology robotics at Johns Hopkins," *Computer Aided Surgery*, vol. 6, no. 6, pp. 360–369, 2001.

[10] "http://www.isys.co.at/."

[11] C. Riviere, J. Gangloff, and M. de Mathelin, "Robotic compensation of biological motion to enhance surgical accuracy," *Proceedings of the IEEE*, vol. 94, no. 9, pp. 1705–1716, 2006.

[12] B. Maurin, B. Bayle, O. Piccin, J. Gangloff, M. de Mathelin, C. Doignon, P. Zanne, and A. Gangi, "A patient-mounted robotic platform for ct-scan guided procedures," *IEEE Transactions on Biomedical Engineering*, vol. 55, no. 10, pp. 2417–2425, 2008.

[13] G. Duchemin, P. Poignet, E. Dombre, and F. Pierrot, "Medically safe and sound, human-friendly robot dependability," *IEEE Robotics Automation Magazine*, vol. 11, no. 2, pp. 46–55, June 2004.

[14] M. Vermeulen and M. Wisse, "Intrinsically safe robot arm: Adjustable static balancing and low power actuation," *International Journal of Social Robotics*, vol. 2, no. 3, pp. 275–288, 2010.

[15] L. Esteveny, L. Barbé, and B. Bayle, "A new indirect actuation principle for safe physical human-robot interactions," in *ASME 2013 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, Portland, USA, 2013.

[16] S. Mahalingam and A. Sharan, "The optimal balancing of the robotic manipulators," in *IEEE International Conference on Robotics and Automation*, vol. 3, April 1986, pp. 828–835.

[17] J. Herder, "Energy-free systems. theory, conception, and design of statically balanced spring mechanisms," Ph.D. dissertation, Delft University of Technology, 2001.

[18] T. Ylikorpi and J. Suomela, "Ball-shaped robots," in *Climbing & Walking Robots, Towards New Applications*, I. Education and Publishing, Eds., 2007, p. 546.

[19] V. Van der Wijk and J. Herder, "Force balancing of variable payload by active force-balanced reconfiguration of the mechanism," in *ASME/IFToMM International Conference on Reconfigurable Mechanisms and Robots*, June 2009, pp. 323–330.

[20] B. Wisse, W. van Dorsser, R. Barents, and J. Herder, "Energy-free adjustment of gravity equilibrators using the virtual spring concept," in *IEEE 10th International Conference on Rehabilitation Robotics*, june 2007, pp. 742–750.

[21] R. Barents, M. Schenk, W. van Dorsser, B. Wisse, and J. Herder, "Spring-to-spring balancing as energy-free adjustment method in gravity equilibrators," *ASME Conference Proceedings*, pp. 689–700, 2009.