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HUMAN-ORIENTED ROBOTS PASSIVE COMPLIANCE ADJUSTMENT APPROACH

Dimitar Chakarov, Mihail Tsveov

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Abstract

Human-oriented robots should be human-friendly, safe and impact-free. The present work is devoted to the problem of adjustable compliance realization during the human-friendly robots design. An approach of joint compliance adjustment based on torsion spring is shown in this investigation. One original design decision of the adjustable compliant joint is revealed. A model and an algorithm are built for synthesis of end effector compliance of a robot with 3 controllable compliant joints. Simulations were carried out to adapt compliance along motion trajectory. A dynamic assessment of compliant robot behaviour is performed.

Key words: human-oriented robots, adjustable compliant joint, torsion spring, end effector compliance adjustment

1. Introduction. Robots in the future will not only fulfil industrial tasks, but also operations related to mutual interaction between the robot and the human beings. In this context, the next generation of robots must be designed in such a way that all contacts with human beings to be injury-free. The basic problem is compliance motion realization during the design of the so-called human-friendly robot.

The first studies are based on an active approach – only by sensors, software and feedback control. The main problem of this approach is a low delayed security for the human when there is an unexpected collision.

Passive compliance, being independent with servo-responses, is reasonable for the implementation of increased safety for human-oriented robots. In such robots, the so-called "serial elastic actuation" is often used [1]. A disadvantage of the elastic actuator is that it possesses a low frequency range for control due to the big elastic link compliance.

New joint drives with controllable compliance are developed in order to remove this disadvantage. Controllable compliance joints are designed using two actuators – one for position control and the other one for compliance control. There are different approaches to control the physical compliance, for example, the Structural Controlled Compliance [2]. In this study, a special mechanism is used for the compliance adjustment that changes one of the structural spring parameters.

In the so-called Mechanically Adjustable Compliance [3], the variation of the compliance is based on the pre-tension variation of the torsion spring situated in the lever mechanism or on the change of the characteristic of the supporting mechanism [4]. In the solution: compact variable stiffness actuator [5], the actuator uses a cam-based lever arm with variable pivot for stiffness adjustment.

The objective of the work presented in this paper is to develop a new approach of compliance adjustment according to passive approach, which to allow a wide range of stiffness regulation, increased safety for the human and precise positioning.

2. Joint compliance adjustment approach based on torsion leaf spring. The objective is fulfilled by means of a constructive implementation of adjustable compliance joint [6], based on a torsion spring as shown in Fig. 1.

The joint includes housing C on which an axel rests, one end of which is connected with a torsion spring L, and the other end is connected with the housing of the motor M_1 with reducer R. At the end of the reducer R is located an output arm A. A deformation measuring sensor S_1 for the torsion spring L is located on the housing. A second gear motor M_2 drives a lead screw W and a barrier B mounted on the screw W, which clamps the torsion spring. Compliance is controlled by altering the length of the torsion spring L with thin rectangular section. Angular position of the effector body (arm) A is controlled using motor M_1.

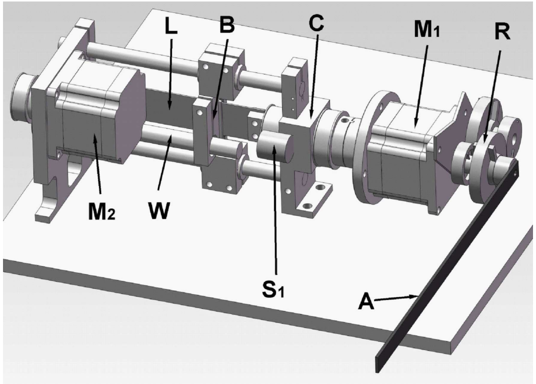


Fig. 1. Adjustable compliance joint design with torsion spring

The basic characteristics that define the design of the compliant joint are the size of elastic deformation in the joint and the size of joint stiffness change.

Deformations in the joint are represented by the angle of twist φ on the axis of the leaf spring with width h and thickness t. When $h/t > 10$, the angle of twist of the torsion spring is determined by the equality [1]:

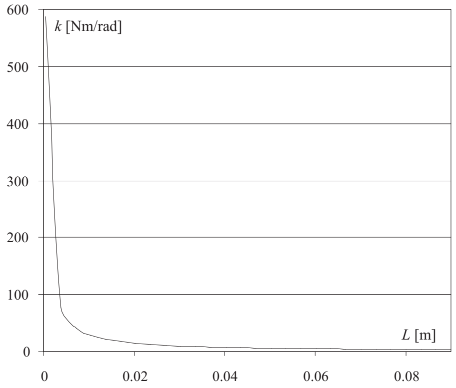
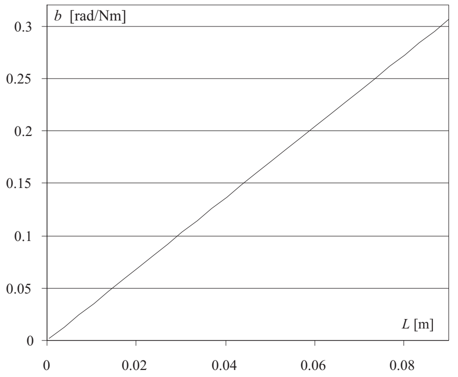
$$\varphi = \frac{3TL}{ht^3G}, \tag{1}$$

where: T is the load torque along the spring axis; L is the active spring length; G is the shear modulus of rigidity.

Joint torsion spring stiffness expresses the ratio of the loading torque M to

Table 1

Structural parameters effect of a length L on spring stiffness and compliance variation

k [Nm/rad]	*b* [rad/Nm]
	

the received angular spring deformation (1):

$$k = \frac{T}{\varphi} = \frac{ht^3G}{3L}. \tag{2}$$

Compliance as a reciprocal function of stiffness $b = 1/k$.

An influence of the structural parameters of a length L, on the stiffness and the compliance change of the spring was studied according to (2). A leaf spring is selected with output parameters: material – titanium alloy Ti-8Mn annealed with modulus of rigidity (shear modulus) $G = 4.910^{10}$ N/m^2 and bending strength (Yield strength) 8.1 10^8 N/m^2. Table 1 shows the results in change of the structural parameters length in the range of $L = [0.294\ 10^{-3} - 0.09]$ m with respect to values of other parameters: thickness $t = 0.001$ m and width $h = 0.018$ m. The range of stiffness variation is $k = [1000 - 3.26]$ Nm/rad, and of the compliance $b = [0.001 - 0.30612]$ rad/Nm.

The spring length L creates a proportional impact on the joint compliance and a reciprocal influence on the stiffness (2). For values of the length L near 0 and the inverse function (2) gives a theoretically infinite high stiffness. This property is the foundation for creation of adjustable compliant joint, where compliance can be reduced to 0.

3. Robot end effector (EE) compliance adjustment. A robot with 3 adjustable compliance joints (ACJ) is revealed. The robot includes a three-limb lightweight arm driven by cable transmissions of three adjustable compliance joints located at the base (Fig. 2).

In the built up kinematics model, positions in the joints and those of robot end effector are calculated using homogeneous coordinate transformations in a programming environment Matlab, a relationship between the speeds – using Matlab function Jacobian – $J(q)$. The relationship between the joint torques

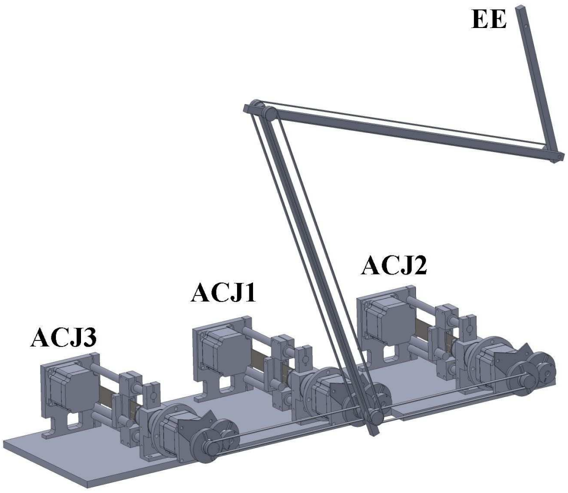


Fig. 2. Robot with three adjustable compliance joints (ACJ1, ACJ2, ACJ3) located at the base

and the forces of the end effector is found at static equilibrium, according to the principle of virtual work, and using the Jacobian.

Changing these torques and forces with reference to the respective displacements gives the matrix relation [7] between the joint stiffness K and the rigidity of the end effector K_0:

$$K_0 = J^{-T} L^T K L J^{-1}. \tag{3}$$

Above L denotes a matrix with permanent members that transforms joint coordinates to compliant drives axes at the base. Inverting the above equation gives the link between compliances:

$$B_0 = J L^{-1} B L^{-T} J^T. \tag{4}$$

Here, B is a matrix of compliance in the controllable joints:

$$B = \begin{vmatrix} b_1 & 0 & 0 \\ 0 & b_2 & 0 \\ 0 & 0 & b_3 \end{vmatrix}. \tag{5}$$

B_0 is (3×3) compliance matrix of robot EE in the plane, which includes (2×2) linear compliance matrix in:

$$B_0^L = \begin{vmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{vmatrix}. \tag{6}$$

To achieve security in the interaction with people and at work in indeterminate environment, the robot EE compliance must be specified to a desired value. Since the matrix of linear compliance (6) is symmetrical, it possesses three independent members b_{11}, b_{22} and b_{12} , which must be specified. According to (4), we can get a system of three linear equations with three unknowns: b_1, b_2 and b_3 – the components of the joint compliance (5).

To visualize the end effector compliance in all directions, the matrix of the linear compliance is represented graphically by an ellipsoid of compliance. Ellipsoid presents graphically linear displacements of end effector under the influence of a single force applied, $P = (\cos\beta; \sin\beta)$, $\beta = \{0; 2\pi\}$. Ellipsoid of compliance is characterized by the sizes of the two main axes, corresponding to the two main values of (6) and the orientation of the ellipsoid, corresponding to the main direction of (6).

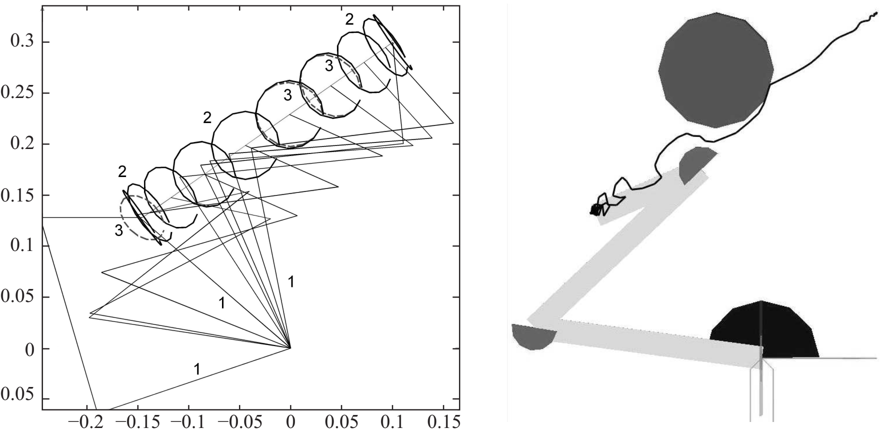
Algorithm and computer program using Matlab are created, where according to (4) the program specifies the desired compliance of robot EE, set by the two major compliances $B_1 = 1/K_1$ and $B_2 = 1/K_2$ and the angle of orientation of the ellipsoid α. Joint compliances $b_1 = 1/k_1$, $b_2 = 1/k_2$ and $b_3 = 1/k_3$ are defined within the limits of their physical change. The solution is improved by optimizing the last robot unit orientation.

Computer experiments are carried out to adapt the compliance in motion trajectory. In ongoing experiments, arm limbs are with lengths: 0.5 m; 0.5 m and 0.2 m, and stiffness in controllable joints k_1, k_2, k_3 is changed in a range $[5; 1000]$ Nm/rad.

In one of these experiments, robot EE moves along a rectilinear trajectory. The main stiffness K_1 and K_2 are given. One of them is a tangential to the trajectory and varies according to the speed, higher at the beginning and at the end of the trajectory $K_1 = 5000$ N/m and low in the middle of the trajectory $K_1 = 300$ N/m. The other one is a normal to the trajectory with a constant size $K_2 = 300$ N/m (Fig. 3*a*). For the successful problem solution, each point of the robot trajectory crawls with 30 possible angles of orientation of the end limb, in order to select the optimization.

In Fig. 3*a*) the calculated optimal positions of the robot limbs are marked with 1; 2 are the desired ellipsoids and 3 (dotted) are the achieved ellipsoids.

The dynamic simulations at kinematics and power constraints are performed by the use of the optimal parameters obtained in the synthesis. Simulations are carried out using the software package SOLID DYNAMICS'04. Movement along



a) *b*)

Fig. 3. Adjustment of compliance along a straight trajectory: a) ellipsoids of compliance and optimal positions of the limbs; b) simulation of the trajectory at impact obstacle

a straight trajectory is defined with a law of amending the compliance, similar to that in Fig. 3*a*).

In the presence of an obstacle in the middle of the path, as shown in Fig. 3*b*), compliance in a normal direction allows to deviate and to overcome the obstacle without blocking or recalculating the trajectory. Low compliance in tangential direction allows accurate positioning at the end of the trajectory.

5. Conclusion. In this work a new approach is presented of compliance adjustment suitable for human-oriented robots. Constructive solution of a compliant joint based on torsion spring is shown in this investigation.

In this work, a robot with three adjustable compliance joints is considered. A model and an algorithm for the synthesis of desired end effector compliance are presented. Simulations for adjustment of the end effector compliance are carried out.

The created compliant robot with the proposed joint presupposes a high motion robustness with respect to unexpected disturbances on the one hand, and a natural human safety on the other.

The proposed solution can be used in human oriented devices as service robots, medicine robots (in surgery and rehabilitation), wearable robots, robots for entertainment (toys, pets, guides) and others.

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Institute of Mechanics
Bulgarian Academy of Sciences
Acad. G. Bonchev St, Bl. 4
1113 Sofia, Bulgaria
e-mail: `mit@imbm.bas.bg`, `mtsveov@abv.bg`