Training of robot to assigned geometric and force trajectories

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Abstract. The features of training by demonstration in robotics for restorative medicine are considered in the article. They are caused by the fact that during training the robot interacts with patient's soft tissue. The regime of training by demonstration is more natural for physician than training of force points using the manual by physician. Also the training by demonstration is more precise method of input of assigned geometric and force trajectories.

Key words: force trained points, training by demonstration, force sensors, soft tissue deforming, geometric and force trajectories.

1 Introduction

Position/force control is necessary for some procedures of restorative medicine robotics. They are various massage movements of extremities in joints [1, 6] and ultrasonic diagnostics. Kernel of these science works is robot mechanical noninvasive interaction with living, biological, viscous elastic, nonlinear soft tissue [4]. The soft tissue elasticity and thickness of every patient can not be determined beforehand.

It is necessary to solve the following tasks of control:

- to generate and to remember set of points characterizing form and state of soft tissues,
- to perform the manipulations on soft tissues using training points,
- to change manipulations kind to achieve necessary patient's psychological state.

The noninvasive mechanical influences at position/force control are used to solve the first problems.

The position/force aim is the following [4, 1,12]:

$$\mathrm{X}(t) \rightarrow \boldsymbol{X}_0(t) \text{ and } \boldsymbol{F}(t) \rightarrow \boldsymbol{F}_0(t), \tag{1}$$

where $\boldsymbol{X}_0(t)$ and $\boldsymbol{F}_0(t)$ are assigned geometric and force trajectories, $\boldsymbol{X}(t)$ and $\boldsymbol{F}(t)$ are real geometric and force trajectories. At the same time the following equation is performed on a given trajectory:

$$\mathbf{F}_0(t) = f(\mathbf{X}_0(t)) \, . \tag{2}$$

Further the various input methods in robot $\boldsymbol{X}_0$ (t) and $\boldsymbol{F}_0$(t), namely, training methods will be considered.

In the second section the special case of robot training by showing along tool axis for force point getting is considered, in the third and fourth sections the general spatial case of training is given.

2 Training with the help of force points

The values of $X_0(t)$ and $F_0(t)$ can be introduced by separate points and then the interpolation will be performed. They can be force trained points A_i which contain geometric and force information about the interaction of robot tool and soft tissue.

$$A_i = (x, y, z, o, a, t, F_z), \tag{3}$$

where x, y, z are geometric coordinates of robot tool position; o, a, t are geometric coordinates of robot tool orientation; F_z is component of force of the interaction of robot tool and soft tissue [3].

The set of points A_i can be determined experimentally using movement of robot tool by manual or joystick .The block diagram of system of force points training is given on Fig. 1. The system contains drive with inner position feedback. The F'_{z0} is force assigned along robot tool axis in direction normal to the body surface.

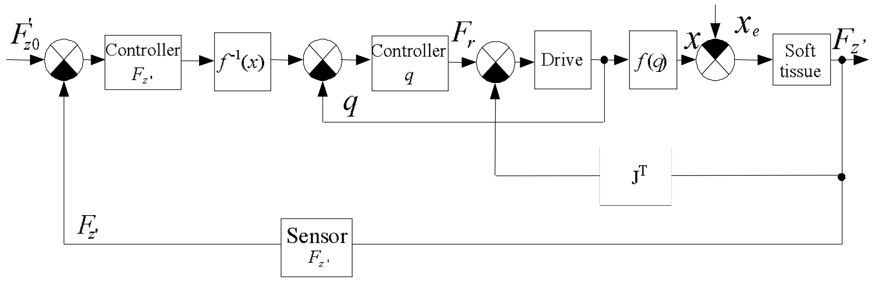

Fig. 1 Block diagram of system of force points training.

The following notations are introduced in Fig.1: $q(t)$ is n-dimensional vector of generalized robot coordinates; $F_r(t)$ is n-dimensional vector of forces (moments) generated by the robot drives; $F(t)$ is m-dimensional vector of generalized forces acting on end-effector from environment; $J(q)$ is m×n Jacobi matrix; $f(q)$ and $f^{-1}(x)$

are the coordinate transformations in direct and inverse kinematic task; $x(t)$ is vector of aim coordinates and $x_e(t)$ is vector of soft tissue relief.

If robot tool does not touch the soft tissue and robot moves in free space then force F=0 (Fig. 2).

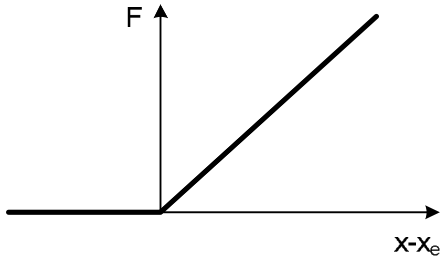

Fig. 2 The static characteristic of soft tissue and robot tool interaction.

The conditions of approaching to assigned forces are shown below.

$$\begin{gathered}\text{if } F_{z'} \le F_{z'0} - \Delta F \text{ then } \Delta z'_{i+1} = \Delta, \\ \text{if } F_{z'0} - \Delta F < F_{z'} < F_{z'0} + \Delta F \text{ then } \Delta z'_{i+1} = 0, \\ \text{if } F_Z \ge F_{Z0} + \Delta F \text{ then } \Delta z'_{i+1} = -\Delta,\end{gathered} \tag{4}$$

where ΔF is deviation from assigned force; Δ is step of moving in tool axis direction.

As in this scheme the moving in tool axis direction is step by step then big steps for rapid motion cause significant force errors. In the Fig. 3 the force caused by discreteness of moving along patient's spine long muscles are shown. The assigned force is equal to 15 N.

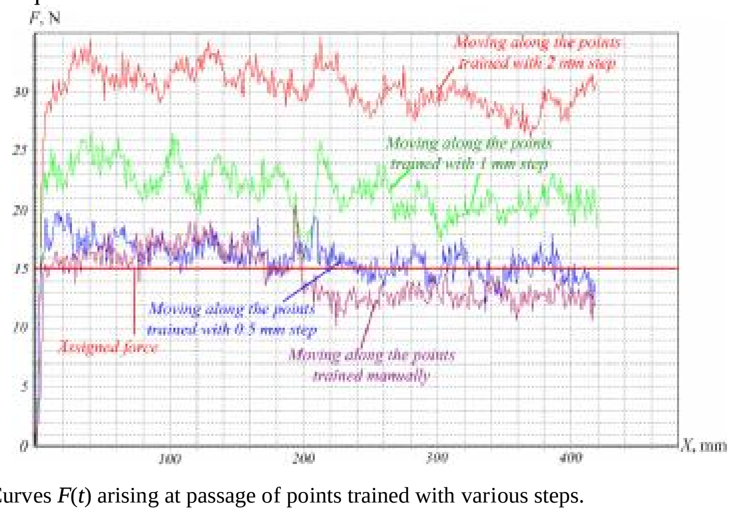

Fig. 3 Curves $F(t)$ arising at passage of points trained with various steps.

Similar experiments were performed on patient's spine long muscles at two back-forward movements. The force curve $F(t)$ for the points trained with step of 0,5 mm and the curve of displacement deviations ξ(t) are resulted on Fig. 4.

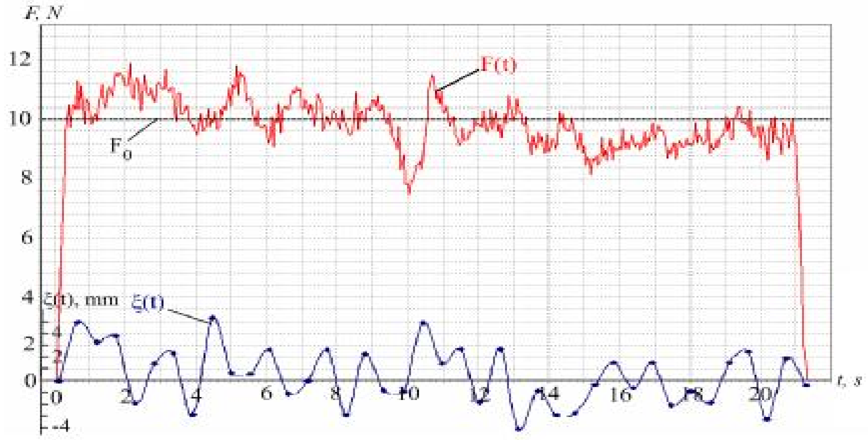

Fig. 4 Curves of $F(t)$ and $\xi(t)$ obtained at passage along patient's long muscles.

3 Training by demonstration

There is another method of obtaining of set of points A_i by demonstration in view of soft tissue deforming [5]. If it is training of geometric points without forces then it is known as training by showing when operator holding robot tool by his hand moves robot in free space [7]. Firstly this is training of paint robots. The experienced house painter moves airbrush by his hand. The special springs help to be unloaded from links weight. The trajectory of hand moving is written and then it is repeated.

Now there are unloading by program methods with using force information. But in contrast to geometric training the robot interacts with environment causing soft tissue force reaction.

The differential equation of robot interacting with soft tissue and masseur's hand has the following form:

$$H(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{h}(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{C}(\mathbf{q}) = \mathbf{F}_r + J^T(\mathbf{q})\mathbf{F}_e, \tag{5}$$

where $H(\mathbf{q}) \in R^{n\times n}$ is matrix of manipulation inertia, $\mathbf{h}(\mathbf{q},\dot{\mathbf{q}}) \in R^n$ is nonlinear function of centrifugal and Coriolis' forces (moments), $\mathbf{C}(\mathbf{q}) \in R^n$ is nonlinear function of gravitational forces (moments), $\mathbf{F}_e \in R^m$ is vector of generalized forces (moments) acting on end-effector from environment.

The mode of slow and smooth massage movements can be approximated to the static one. Then we have:

$$H(\mathbf{q})\ddot{\mathbf{q}} = \mathbf{h}(\mathbf{q},\dot{\mathbf{q}}) = 0, \tag{6}$$

$$\mathbf{C}(\mathbf{q}) = \mathbf{F}_r + J^T(\mathbf{q})\mathbf{F}_e, \tag{7}$$

$$\mathbf{F}_e = \mathbf{F}_0 - \mathbf{F}, \tag{8}$$

where F_0 is vector of forces (moments) from operator's hand.

Finally we have:

$$\mathbf{C}(\mathbf{q}) - J^T(\mathbf{q})(\mathbf{F}_0 - \mathbf{F}) = \mathbf{F}_r\,, \tag{9}$$

where F_r is vector of force (moment) made by robot drives. The forces (moments) acting on robot end-effector are shown on Fig.5 and scheme of training by demonstration in view of soft tissue deforming is given on Fig. 6.

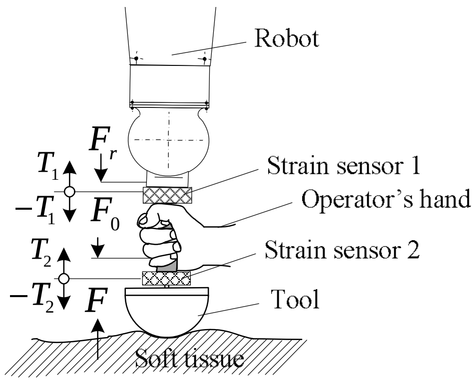

Fig. 5 The forces (moments) acting on robot end-effector.

On Fig. 5 T_1 is vector of forces (moments) measured by upper force sensor, T_2 is vector of forces (moments) measured by lower force sensor.

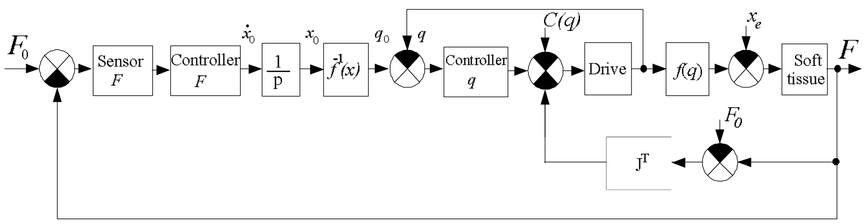

Fig. 6 Scheme of training by demonstration in view of soft tissue deforming.

This system is similar to system of training of force points, but in system of training of force points the force is given by program and in system of training by demonstration the force is given by operator's handle.

If the mass of robot end-effector is concentrated in tool, then the sensors placed above and below the operator's hands will measure various forces.

$$\boldsymbol{T}_1 = \boldsymbol{F}_r = \boldsymbol{F} - \boldsymbol{F}_0 - \boldsymbol{C}(\boldsymbol{q}), \quad (10)$$
$$\boldsymbol{T}_2 = - F + \boldsymbol{C}(\boldsymbol{q}) = -\boldsymbol{F}_0 - \boldsymbol{F}_r \quad (11)$$

The upper sensor measuring force $T_1 \approx F - F_0$ is *sensor F* in system on Fig.6. The lower sensor measuring force $T_1 \approx F - F_0$ can be used for visual observation of the force reaction of soft tissue.

During training the movements in robot joints are recorded from coders as separate training points or as continuous trajectory.

For realization of training by showing the force information from strain sensor located on robot hand isn't single. The force information can be obtained from joint force sensors and converted by Jacobi matrix how it's done in LWR Kuka robot. Also the force information can be obtained from joint drive currents.

4 The system of training by demonstration using measured drives currents for calculation soft tissue resistance forces

The currents of robot drives include some information about load moments. On Fig.7 the system of training by demonstration using measured drive currents for calculation soft tissue resistance forces is given. The block $(J^T)^{-1}(q)$ is necessary for transformation of measured drive currents in currents of aim coordinates system. Then these currents are transformed by converter in forces (moments).

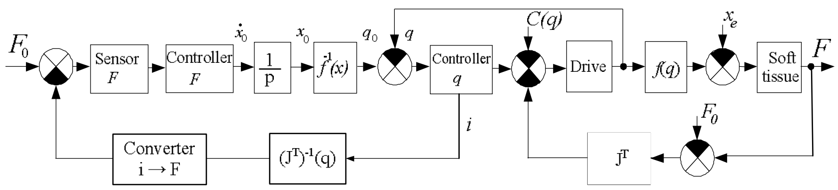

Fig. 7 Scheme of training by demonstration in view of soft tissue deforming using measured drive currents for calculation soft tissue resistance forces.

The idea of using of measured drive currents for calculation soft tissue resistance forces is realized in UR5 and UR10 robots.

5 The features of training by demonstration in view of soft tissues deforming

The ideal massage is when masseur deforms patient's soft tissues by his sensitive hand. As to unload the robot action on masseur's hand completely is impossible then the training of masseur to perform massage techniques by robot tool with interfering robot is a must.

The training by demonstration is example of interaction of robot and human-operator in total working area when robot can work without enclosure. In robotics for restorative medicine the patient and robot interact in total working area also. In contrast to usual ergonomic scheme where robot performs manipulations with technical environment, in this case third component is human also [2]. The scheme of interaction between components of physician-operator, robot, patient is presented in Fig. 8. New connections appear in this three-component system.

The possible connections between components and modes are the following: 1 – command control signals from a physician for change of modes and procedure parameters, including training mode; 2 – use by the physician of the data, received in the previous sessions and knowledge base replenishment (system Medsoft); 3 – psychological influence of the physician on the patient; 4 – manual execution of procedure by the physician (solo or with a robot); 5 – signals of subjective patient's state transmitted to the physician including verbal feedback; 6 – assigned values of forces, movements, velocities for position/force control and nominal date for biotechnical control; 7 – signals of real state of soft tissues for position/force control; 8 – signals of real state of soft tissues for biotechnical control; 9 – signals of individual robot control from patient, 10 – robot action on patient.

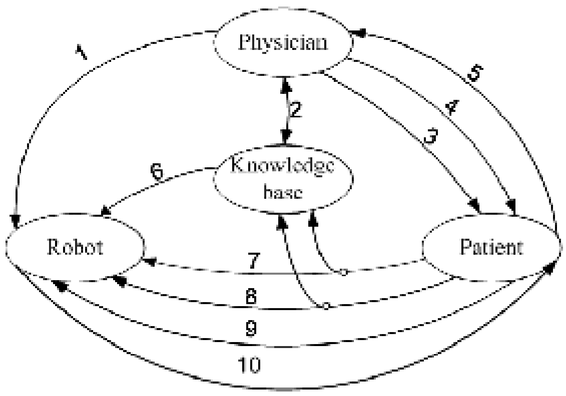

Fig. 8 Scheme of interaction between components of physician-operator system, robot, patient.

The influences, signals and modes given on the scheme form several control counters: automatic position/force control (6+7+10), automatic biotechnical control (6+8+10), command control (1+2+10), manual performing of procedure (4+5), mutual performance of procedure by physician and robot

(1+2+3+4+5+6+7+8+9+10), individual robot control from patient (9+10).

The last mode of individual robot control from patient is similar robot training by operator.

The training of Kawasaki FS-003N robot by demonstration with using six-component strain sensor is shown in Fig. 9. The general form of six-component strain sensor Schunk FTD-Delta SI-330-30 using for training by demonstration and controller is given in Fig. 10.

Fig. 9 The training of Kawasaki FS-003N robot by demonstration with using six-component train sensor.

Fig. 10 Six-component strain sensor Schunk FTD-Delta SI-330-30 and controller.

New relations between the robot and the person arise not only in a medical robotics. In non-structured environments and extreme situations, the robot should be not "stupid" but the intellectual assistant to the person. There are problems of equality in rights of interaction of the robot and the assembly worker on the conveyor, when in unscheduled situations, the assembly worker not only controls the robot but also he adapts to its work, providing both the friendly interface and his own safety. Mutual work of robot and operator is necessary in cosmos condition when the robot repeats the movements shown by operator or the operator controls robot perceiving the force interaction of robot with equipment [8, 9].

6 Conclusions

The training of separate force points has the benefit no requiring expensive six component strain sensor for force measurement. However it is slow training requiring large number of points.

The method of training by demonstration of moving in free space is known in industrial robotics for example for spray painting and arc welding. The method of training by demonstration with deformation of environment can be used for massage. It is more natural and quick method than the training of separate force points.

Both methods have significant drawback requiring immobility of the object on which manipulations are performed. This drawback can be excluded by using dynamic position/force control to correct object movements.

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