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Manipulator Development for Telediagnostics

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***Abstract*—**This paper presents development of the light-weight manipulator with series elastic actuation for medical telediagnostics (USG examination). General structure of realized impedance control algorithm was shown. It was described how to perform force measurements based mainly on elasticity of manipulator links.

***Keywords*—**Telediagnostics, elastic manipulator, impedance control, force measurement.

I. Introduction

MODERN society increasingly requires specialized medical care. Unfortunately, in most countries there is a lack of physicians. This situation is steadily deteriorating and this is particularly evident in a limited number of specialists who are not always available to the medical unit due to geographical (e.g. provincial hospitals), time (after regular working hours) or other logistic constraints. This circumstance provides an incentive for the development of many types of medicine-related services performed remotely ranging from Telepsychiatry, Telerehabilitation, Teledentistry, etc. to Telesurgery.

Usually a successful medical treatment depends on a timely and correct diagnosis which is crucial in typical emergency situations. Specialist (a doctor) needs some time to get to patient from home or from another hospital. If doctor could perform the diagnostics remotely, and e.g. make a decision about a surgical intervention, the hospital staff could use the time during which the doctor is travelling and prepare the patient. Currently there exist no devices enabling complete remote medical examination and diagnostics based on contemporary medical standards [1].

Presented work is a part of the project which addresses telediagnostics in clinical environments. Multifuntional robotic system, which will allow performing a real remote physical and ultrasonographic (USG) examination, was designed. The system, see Fig. 1, consists of a mobile robot operating in a hospital, and a remote interface placed at the doctor's location. The role of the mobile robot is twofold: firstly- it acts as a full embodiment of the doctor; secondly it is an intelligent robot system equipped with advanced perception, reasoning, and learning abilities.

One of the most important elements of the system (i.e. mobile robot part) is manipulator with palpation and USG effector. Cable-driven 6DoF manipulator to form wrist, elbow and shoulder was developed. The drives are based on series elastic actuation principles and form a lightweight and safe solution. To achieve semi-autonomous functionality of the manipulator, a special control system PC-based real-time operating system and hardware security controller were designed.

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II. Design of Elastic Manipulator

A. Manipulator Requirements

In industrial or laboratory settings the safety of the human operators/users can be guaranteed through barriers. The safety requirements increase drastically when robots physically interact with humans, as in our case, since a single malfunction can endanger the life or health of the patient. Therefore it is extremely important to take safety into account during each phase of the design and development. Unfortunately, there exists no industry-standard approach to designing safety-critical robots for physical human-robot interaction. De Santis et al. formulated an atlas of physical human robot interaction with special focus on safety and dependability [2].

Based on the above information, the following guidance should be taken into account during the design of a robot arm:

1) the inertia of the moving parts should be kept as low as possible by means of lightweight design by locating the drives in the robot base and transmitting the mechanical power to the joints using cable actuation - reduction of the potentially catastrophic consequences of the robot hitting a human,
2) robot surface should be covered with soft material; no sharp elements should be on the robot surface [3],
3) safe limits for the maximum moving weight and velocities of the arm have to be found by simulation and ensured on the robotic system [4],
4) the drives should be torque limited and backdrivable so that the user may change the robot position just by touching and moving it with bare hands,
5) human body parts (i.e. fingers, hands) and clothing parts should be protected against clamp in between joints, cables or any other protruding elements,
6) user should be protected against electric shock -ideally, no voltage higher than 48 V DC should be present in the robot,
7) robot should recognize the interaction forces exerted by the surrounding humans or objects not only at the end effector or at the joints - adequate force sensors and manipulator workspace should be comparable to that of a human arm,

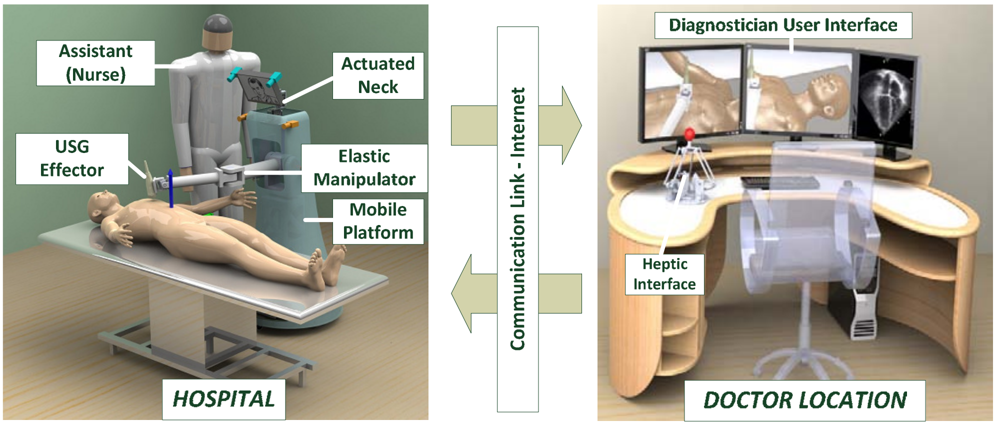

Fig. 1 Diagnostic system overview

8) overall weight should be maximum 5kg and payload of 3 kg.

The above requirements are not acceptable in the industrial robotic design, where the accuracy, speed and durability in long term operation are the predominant, so the industrial manipulators couldn't be used. Accordingly to [5] our robot has to sacrifice high accuracy and performance in favor of safety so the search area of possible existing and suitable manipulator was rehabilitation and care robotics. The following robot arms were investigated: DLR-III Lightweight Robot [6], Barrett WAM-Arm [7], Kinova JACO [8], Assistive Robotic Manipulator iARM [9], BioRob-Arm [10], Meka A2 Compliant Arm [11], Robotnik modular arm and ACCREA arms [12]. Their parameters are summarized in Table I. However, all these arms do not meet the requirements as mentioned above, e.g. due to too high weight or size, too small workspace, or they are not available.

TABLE I
MANIPULATORS AND THEIR PARAMETERS

Parameter	Unit	DLR III	Barrett WAM	KINOVA	iARM	AMOR	Biorob	Meka A2	Robotnik	*ACCREA*
Degrees of freedom	-	7	7	6	6	7	4	7	7	7
Total weight	kg	14	27	5	9	9	4.4	11.4	19	10
Mass of moving parts	kg	no data	no data	5	no data	no data	0	1	11.4	5
Maximum load	kg	7	3	1.5	1.5	2.5	2	2	no data	2.5
Reach	cm	93.6	100	90	90	95	70	no data	130	80
Backdravibility	-	Yes	Yes	Yes	Yes	no data	Yes	Yes	Yes	Yes
Absolute position tolerance	mm	no data	2	8	no data	2.5	no data	no data	no data	4
Relative position tolerance	mm	no data	0.2	1.6	no data	1.3	no data	0.2	0.5	1
Prices	EUR	90000	50000	40000	n/a	35000	30000	60000	50000	n/a

B. Mechanical Design

Given the above design requirements, 6DOF cable-driven manipulator was designed. The links of the manipulator are actuated using actuators with serial elasticity. Overview of this manipulator presents Fig. 2. All heavy motors are placed in the manipulator base. Compliant transmission mechanically decouples the lower link inertia from the heavy motors, which leads to even less apparent inertia during impacts. The joints are multi-actuated using differential kinematic structures, so that an uncontrolled behavior of one motor will not be able to produce dangerous motion of the link. Second joint (shoulder) of manipulator is passively gravity compensated. Gear reduction ratios were reduced as much as possible to ensure backdrivability of the actuators. In order to realize force control algorithms, there are linear springs (two per each joint) mounted in series with cables, in similar way presented in work [10]. It requires use of two encoders at each joint, one mounted on the motor shaft and the second (more precise) directly on the joint. This solution makes it possible to eliminate expensive force sensor JR3mounted at the end of the manipulator or to support results of his measurements in the control algorithm.

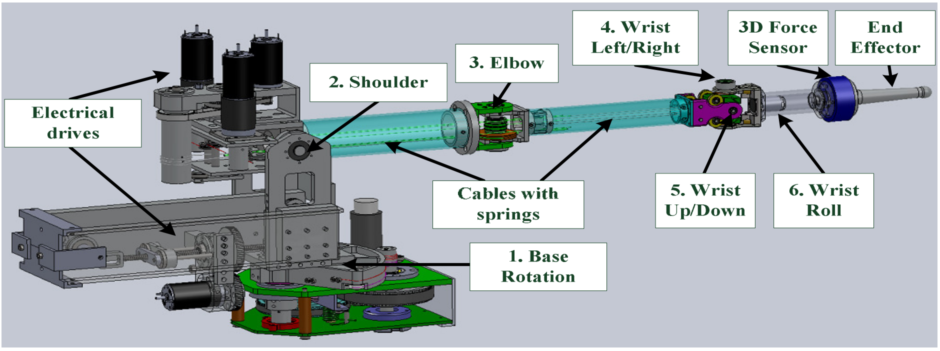

Fig. 2 Design of the 6 DoF elastic manipulator

The Denavit-Hartenberg parameters for the manipulator are listed in Table II, the corresponding set of frames is shown in joints $\boldsymbol{q}$ (vector of angular positions or velocities in joint space and the motors shafts Θ (vector of angular positions or velocities in motor space) was described in (1) :

$$\boldsymbol{q} = \boldsymbol{G} \cdot \boldsymbol{\Theta} \tag{1}$$

where $\boldsymbol{G}$ is a gear ratio and coupling matrix as in (2)

$$G = \begin{bmatrix} G_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & G_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & G_3 & 0 & 0 & 0 \\ 0 & 0 & -G_3 & \frac{G_4}{2} & \frac{G_5}{2} & 0 \\ 0 & 0 & 0 & \frac{G_4}{2} & \frac{G_5}{2} & 0 \\ 0 & 0 & 0 & -\frac{G_4}{2} & -\frac{G_5}{2} & G_6 \end{bmatrix} \tag{2}$$

where G_i is gear ratio of i-th joint.

TABLE II
MANIPULATOR DENAVIT-HARTENBERG PARAMETERS

Joint no	*Link offset* a_i *(mm)*	*Link twist* α_i *(rad)*	*Link length* l_i *(mm)*
1	195.0	$\pi/2$	0
2	0	$-\pi/2$	293.3
3	0	0	312.0
4	0	$\pi/2$	0
5	0	$\pi/2$	0
6	194.0	0	0

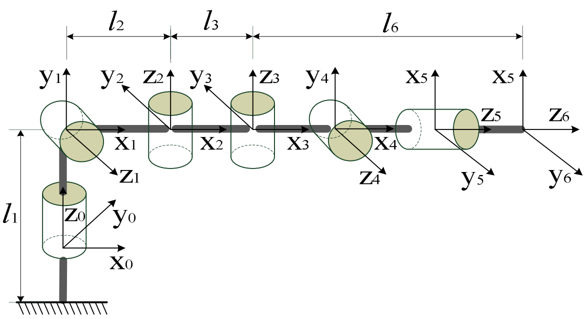

Fig. 3 Kinematic structure and link coordinate systems of the 6 DoF elastic manipulator

III. MANIPULATOR CONTROL SYSTEM

The main task of the control system is the implementation of telediagnostics task (USG), i.e., movement of the end-effector over the examined part of patient body, according to the position, orientation and force desired by the operator (doctor). In that case the most suitable is use of impedance control algorithm [12]. In order to realize above task, real time control with sampling period 1ms (or less) and accurate manipulator dynamic model should be implemented [12].

A. Control System Structure

General structure of designed control system presents Fig. 4. This structure consists of three main elements:

1) controlled object - elastic manipulator,
2) controller - PC computer with real time operation system (RT Preempt or Xenomai), two multifunctional analog/digital I/O cards, force sensor JR3 card and implemented control algorithm,
3) hardware safety system and motor current controllers (servoamplifiers).

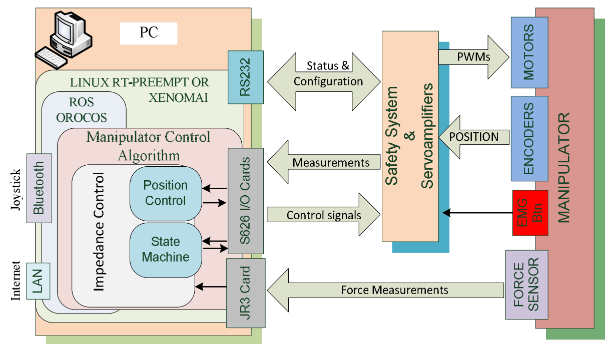

Fig. 4 Structure of manipulator control system

The main task of the safety system is to protect the user in case of emergency, mainly caused by different types of device malfunctions in the control system, as failure of: encoders (e.g. open or short circuit), servoamplifiers (overload or overvoltage), PC controller (hang or crash) and the detection and response to other irregularities as such as joint overspeed.

The basic components of control algorithm, which was developed using Matlab-Simulink software, are impedance control algorithm and state machine. The state machine defines all kinds of situations in which the manipulator can be found starting from initialization of the security system and joints homing, through mode and task selection adequately to the demands of the operator or assistant and ending at the appropriate reaction in failure situation. The impedance control algorithm strategy presents Fig. 5. As mentioned in [12] the goal of the impedance control is to make the end-effector behave as an linear and decoupled mechanical impedance characterized by a virtual mass $\boldsymbol{M_p}$, damping $\boldsymbol{D_p}$ and stiffness $\boldsymbol{K_p}$ matrices with regard to measured contact Cartesian force $\boldsymbol{F}$. This can be written as follows:

$$\boldsymbol{M}_p \cdot \boldsymbol{p}'' + \boldsymbol{D}_p \cdot \boldsymbol{p}' + \boldsymbol{K}_p \cdot \boldsymbol{p} = \boldsymbol{F} \tag{3}$$

where $\boldsymbol{p}$ denotes the difference between desired $\boldsymbol{p_d}$ and compliance $\boldsymbol{p_c}$ frames (position and orientation). The compliant frame describes the end-effector position and orientation when it is in contact with the environment (patient) and then impedance controller modifies desired frame according to measured forces. When there is no contact $\boldsymbol{p_c}$ is identical with $\boldsymbol{p_d}$. This algorithm requires a valid measurement of the force exerted on the end-effector. To achieve this without force sensor JR3 (based on elasticity of each joint drive cables with springs) accurate manipulator dynamic model is required.

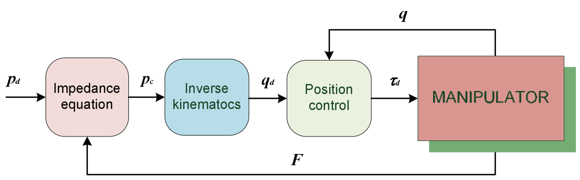

Fig. 5 Impedance control strategy

B. Manipulator Dynamic Model and Force Measurement

The general dynamical model of rigid manipulator can be written in the form:

$$\boldsymbol{M}(\boldsymbol{q}) \cdot \boldsymbol{q}'' + \boldsymbol{C}(\boldsymbol{q},\boldsymbol{q}') \cdot \boldsymbol{q}' + \boldsymbol{D} \cdot \boldsymbol{q}' + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{\tau} - \boldsymbol{J}^T \cdot \boldsymbol{F} \tag{4}$$

where $\boldsymbol{q}$ is the vector of joint positions (angles), $\boldsymbol{M}$ is the inertia matrix, $\boldsymbol{C(q,q')*q'}$ is the vector of Coriolis and centrifugal torques, $\boldsymbol{D}$ is diagonal friction matrix, $\boldsymbol{g}$ is a vector of gravitational torques, $\boldsymbol{\tau}$ is the vector of driving torques, $\boldsymbol{J}$ is the Jacobian matrix relating joint velocities $\boldsymbol{q'}$ to the vector of end-effector Cartesian velocities $\boldsymbol{x'}$. Because of relatively slow motion of manipulator parts vector $\boldsymbol{C(q,q')*q'}$ can be assumed as negligible and then (4) will be in form:

$$\boldsymbol{M}(\boldsymbol{q}) \cdot \boldsymbol{q}'' + \boldsymbol{D} \cdot \boldsymbol{q}' + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{\tau} - \boldsymbol{J}^T \cdot \boldsymbol{F} \tag{5}$$

According to [10], in case of elastic actuator, driving torques $\boldsymbol{\tau}$ can be calculated as:

$$\boldsymbol{\tau} = \boldsymbol{k}_e \cdot (\boldsymbol{q}_m - \boldsymbol{q}) \tag{6}$$

where $\boldsymbol{k}_e$ is the vector of elasticity factors, $\boldsymbol{q_m}$ is the vector of drive shaft positions.

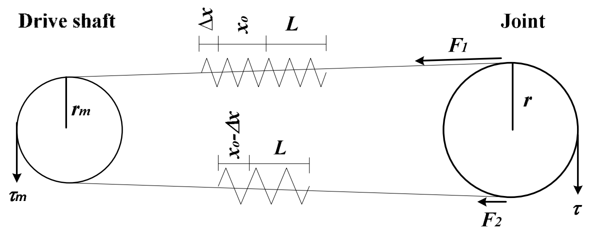

Fig. 6 Force measurement principle on the base on manipulator elasticity

Every spring is pretensioned which causes spring elongation x_0. According to situation presented on Fig. 6 torque τ is calculated as:

$$\tau = r \cdot (F_1 - F_2) \tag{7}$$

where r is the radius of joint pulley, F_1, F_2 are upper side and lower side forces. The difference between the values of both forces F_1- F_2 depends on spring elongation Δx and it is calculated in two cases: first when $|\Delta x| \le x_0$

$$F_1 - F_2 = 2 \cdot k \cdot \Delta x \tag{8}$$

and second when $|\Delta x| > x_0$

$$F_1 - F_2 = k \cdot (\Delta x \pm x_0) \tag{9}$$

where k is the spring constant and sign before x_0 depends on the spring which is stretched the more. Spring elongation Δx is obtained as:

$$\Delta x = r_m \cdot q_m - r \cdot q \tag{10}$$

where r_m is the radius of motor shaft pulley.

Cartesian force $\boldsymbol{F}$, at the end-effector, can be calculated through equation obtained from (5):

$$\boldsymbol{F} = (\boldsymbol{J}^T)^{-1} \cdot (\boldsymbol{\tau} - \boldsymbol{M}(\boldsymbol{q}) \cdot \boldsymbol{q}'' - \boldsymbol{D} \cdot \boldsymbol{q}' - \boldsymbol{g}(\boldsymbol{q})) \tag{11}$$

where $\boldsymbol{M_e}$, $\boldsymbol{D_e}$ and $\boldsymbol{g_e}$ are the same matrices and vectors as in (5) but with the exclusion of the impact of this part which relates to the drive (i.e. the engines and gearboxes).

Series of experiments were carried out in which were compared the measured forces obtained using described above method and the measurements obtained from force sensor. These experiments were made in different conditions i.e. different position and orientation of end-effector and different force direction. These experiments were performed under different conditions, i.e. different positions and orientations of the end-effector and for different directions of impacts. Fig. 7 presents force measurements in case of force acting parallel to the direction x_0 (Fig. 7 (a)) and in case of force acting parallel to the direction y_0 (Fig. 7 (b)).

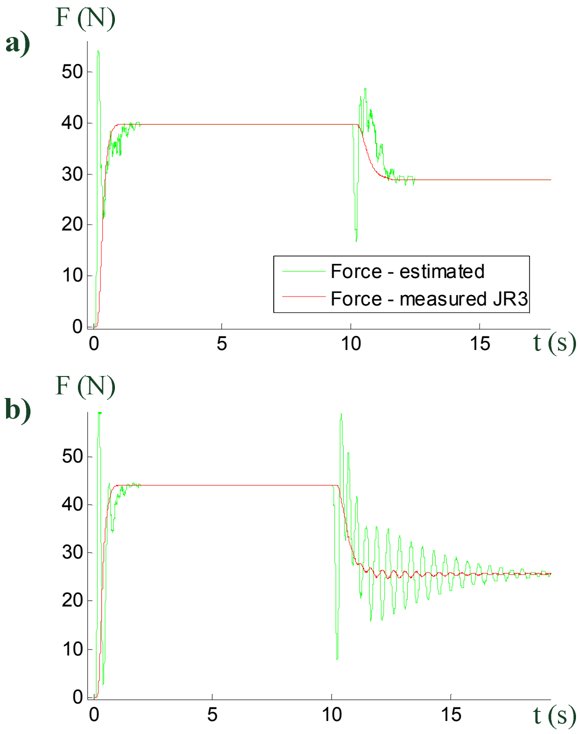

Fig. 7 Experimental results: (a) force waveforms in case of force acting parallel to the direction x_0, (b) force waveforms in case of force acting parallel to the direction y_0

IV. Conclusion

This paper presented the development of elastic manipulator for medical telediagnostics. We pointed out how desired is to design new type of manipulator in case of lack commercially available manipulator. The control system with impedance control algorithm was designed for this manipulator. In order to perform force measurements, method which utilizes the flexibility of links was developed. Experiments confirmed the correct operation of the system, especially in steady state. The differences in the waveforms of forces under dynamic conditions are mainly caused due to inaccuracies of the model parameters. In order to use this type of measurement in the control algorithm, the model accuracy should be improved.

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