Mathematical Representation of Haptic Robotic Realization for Artefacts Maintenance

Alexey Bulgakov [a] Andrey Volkov [b] and Daher Sayfeddine [c]

[a] Professor, Dr.-tech-sc., South West State University, Kursk, Russia
[b] Professor, Dr.-tech.sc., Rector, Moscow State of Civil Engineering, Moscow, Russia
[c] Ph.D., South Russian State Polytechnic University, Novocherkassk, Russia
E-mail: [a] a.bulgakow@gmx.de, [b] volkov@mgsu.ru, [c] daher@live.ru

Abstract –

Originally generated from Greek world "*haptikos*", haptic technology is used in many grasping and robotic applications. Commercially, it is widely known solution in videogames and mobile technology. Essentially, haptics is used in medical robots, where the surgeon is located outside of the sterile area and remotely operates vide a direct video connection the robot manipulators, which are holding endoscopes and working elements. Haptics has proven its worth especially for minimal and non-invasive surgical procedures, where the patient care coefficient has increased. As it is directly related to human existence, artifacts may be as sensitive as human life and need extreme care to last for the next generations. Here we could see a possibility to combine haptics with the maintenance of the monuments. In this paper we represent mathematically a haptic robotic concept for artefact maintenance purposes.

Keywords –
Haptics; Telerobotics; Artefact Maintenance

1 Introduction

Haptics is human-machine interface technology aiming to guide a human operator-controller by recreating his tactile sense signals. The realization process is based on applied forces, vibrations or motions fed back to the operator in order to perceive the surrounding world [8]. This terminology is widely used in telerobotics, essentially for semi-autonomous distantly guided mobile robots or manipulators. The biggest success of the haptic implementation is observed in medical field (surgical robots) [6,9]. Therefore it is believed that haptics can be used where machine infinite precision, human flair and passion need to be combined in an integrated work. Historically, polymaths and inventors were blessed with such gift: flair and precision. We appreciate their work by contemplating monuments, old machineries and inventions. Artefacts are very important to humanity. In fact, a small piece of stone can tell a story of a whole generation or race. Human being has appreciated the value of the artefacts and started maintaining them periodically. In a refurbishment workshop, several artists, architects and engineers team up together to conserve the masterpiece.

Looping back to haptics, we see possible integration for this technology in artefacts maintenance. The remote control allows the artist to have a wide-view of the masterpiece and improve its simulation in his mind. In parallel, the mechanical feedback and the robust robotic arms achieve better stabilization of the working tools than the human hand. To proceed with the simulation of this idea, we have firstly to describe the haptic approach in telerobotics.

There exist two major haptic mechanical categories: impedance-type and admittance-type devices. The first is drivable, open loop operated mechanism that has less output force. In contradiction, the latter is non-drivable, closed-loop operated device and has high output force. The effectiveness of each category is evaluated through a factor called transparency or the output impedance. The physical meaning of this factor is the ability to render zero forces with the disturbance of the existing user motion.

Developing criteria and simulators to avoid costly prototyping and experimental comparisons and analyzing each approach are yet to be perfected. However, we can bring to your notice that the impedance-type devices are easier to simulate and more straightforward in opposition to the admittance-type. This is because the latter is inherently non-drivable and particularly because the output impedance is very high in the frequency range above bandwidth of the admittance controller.

2 Related work

Many literatures are oriented to study the haptic mechanism and simulation models. Some researchers have developed methods to analyze the transparency factors. While some of them are difficult to implement due to experimental dependencies [1,2,3], others are more simulation-friendly [4,5].

Choosing a haptic device type depends on the control task to be performed. From this point of view we can characterize these two categories as follows:

a- An impedance control system senses motion developed by the operator (position, orientation) and controls the force on the haptic device. While an admittance control system senses forces commanded by the operator and accordingly controls the motion of the haptic device.

b- For impedance-type devices, any small change in position will cause a very high rise in actuator reaction force. To minimize this effect, we require very high control gain from measured device position to actuator force [8]. At the same time, the high gain value will have implication on the stability, as control gains cannot become infinity high.

On the other hand admittance control was used to manipulate rigid objects. Therefore, the admittance-type device is highly geared. This guides to non-backdrivable effect and generates forces at the end-effectors.

For the paper purposes, we choose to simulate impedance-type haptic device as it can render small masses necessary to work with artefacts. Using the abovementioned definitions developed earlier, we can draw the following comparison that approves our choice.

Table 1. Impedance-type (IT) vs. Admittance-type (AT)

Criterion	IT	AT
Input	Motion	Force
Output	Force	Motion
Render mass	Yes	No
Stiffness	Poor	Capable

Additionally, we would like to mention that the most frequent problem addressed in the literature on haptic devices is the stability problem. Listed below are some of the possible reasons for the stability issue of the haptic devices:

- Coulomb friction;
- Actuator saturation;
- Sensors fidelity;
- Discretization and sampling;
- Joints flexibility;
- Virtual environment dynamics;
- Human hand dynamics.

Addressing all these points is a challenging task. Some of these factors can be neglected for simulation and analysis purposes.

3 Design and control of the haptic device

A haptic device interface represents a challenging design task, as it is required to be light back drivable. In such scenario, the operator feels no resistance in case of free motion of the robotic manipulator. At the same time, it is important that the operator feels the force generated from the virtual environment and not that of the mechanism weight. Hence, the design should address the following criteria:

- Free space is a free motion;
- Solid virtual object must be felt stiff enough;
- Haptic dynamics must not be additional noise on the operator perception of the virtual world.

The minimum stiffness calculated experimentally is calculated around 20 N/cm in order to feel rigid bodies [6].

In table 2 are given solutions addressing the abovementioned design criteria

Table 2. Control solution for haptic design

Criterion	IT
Freedom	Active control
Stiffness	High-bandwidth controller
Dynamic noise	High computation speed

A mechanical requirement to be added to the control task is the saturation requirement. By that, we understand the higher the force applied on the haptic device the larger the force that must be supplied by the actuator.

Typical block diagram for haptic controller is illustrated in fig.1

3.1 Impedance Control Architecture

There are several approaches for impedance control: open loop impedance control, impedance control with feed-forward and feedback terms and impedance control with hybrid compensation. The idea in impedance control is to make the robot to behave as a spring-mass- damper system, which can be described mathematically using the following equation

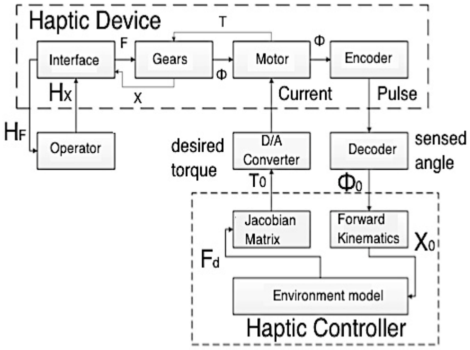

Figure 1. Typical block diagram for haptic controller

$$F = M\ddot{x_{ref}} + D(\dot{x} - \dot{x_d}) + K(x - x_d) \qquad (1)$$

Where F is the force of the environment affecting the robot, *M* is the mass, *D* and *K* are the damping and spring stiffness coefficients respectively. x_d and $\dot{x_d}$ are the desired position and velocity of the robot, while x and $\dot{x}$ are the expected values.

An illustration of the Spring-Mass-Damper is given in figure.2.

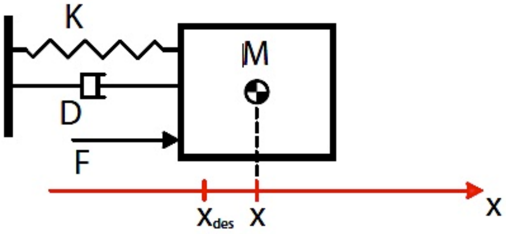

Figure 2. Spring-Mass-Damper concept

If we assume that the acceleration of the robot is equal to the referential acceleration, then using equation (1) we can say:

$$\ddot{x_{ref}} = \frac{F - D(\dot{x} - \dot{x_d}) - K(x - x_d)}{M} \qquad (2)$$

By integrating the acceleration we can obtain the referential velocity and position. Since we have to implement control law, the values of the $\dot{x_{ref}}$ and x_d have to be discretized with reference to a sampling rate *h*. This guides us to write the following equations

$$\dot{x_{ref}}[k] = \sum_{i=0}^{k} \ddot{x_d}[i] * h\,; \qquad (3)$$

$$x_{ref}[k] = x[0] + \sum_{i=0}^{k} \dot{x_{ref}}[i] * h\,; \qquad (4)$$

Where the discrete integration of a signal *u[k]*is defined as $\sum_{i=0}^{k} u[k] * h\,;$

By achieving the discrete integration, it is now possible to design a control system, which is able stabilize a Spring-Mass-Damper system, representing here the haptic robot. The task doesn't seem to be smooth, as it is difficult to imagine how a system with chosen damping and stiffness coefficient will behave. Nevertheless, it is possible to compare the characteristic polynomial of the system transfer function W_{DS}(p) with characteristic polynomial of an ideal aperiodic second order transfer function W_{2s}(p); where:

$$W_{DS}(p) = Mp^2 + Dp + k; \qquad (5)$$

$$W_{2s}(p) = p^2 + 2\zeta\omega p + \omega^2 \qquad (6)$$

Where $\omega -$ is the eigenfrequency of the sring-mass-damper system; $\zeta -$ is the damping ∈ [0;1] and $p -$ is the Laplace operator.

From equations (5) and (6), we can obtain the following equalities:

$$D = 2\zeta\omega; \qquad (7)$$

$$k = M * \omega^2; \qquad (8)$$

3.2 Simulation Results

The haptic device is usually a robotic arm manipulating tools. Therefore, the end effector mechanism or the grasping body are important to us. Nevertheless, the behaviour of the remaining joints is essential to have stable grasping or precise execution [7]. In this paragraph, we illustrate the robotic arm with 5 joints. This design is called an Elbow-Manipulator (figure.3.). It consists of the following joints: base fixation on wheels, body, shoulder, elbow and forearm.

Based on the Force/Torque relationship, the interaction of the manipulator with the surrounding environment will produce forces and moments on the grasping element. We designate F as the vector of forces and torques. Hence we can write:

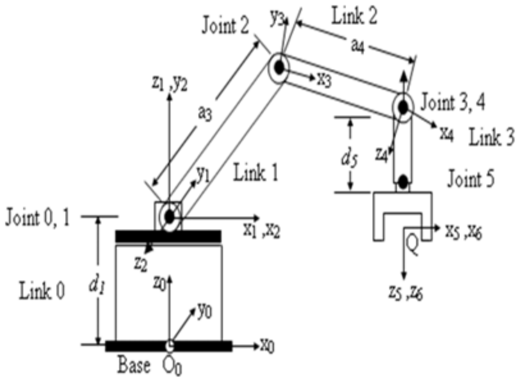

Figure 3. Representation of kinematic structure of elbow-manipulator

$$F = [F_x \quad F_y \quad F_z \quad n_x \quad n_y \quad n_z]^T; \qquad (9)$$

Where $F_x \quad F_y \quad F_z -$ are the components of the force and $n_x \quad n_y \quad n_z -$ components torques on the grasping tool accordingly.

We donate τ for vector of joints torques, δ is the displacement of the end effector caused by the vector F and γ is the corresponding virtual joints displacement. We can write:

$$\delta = J(q) * \gamma; \qquad (10)$$

Where $J(q) -$ is the Jacobian of the manipulator.

The virtual work of the system is given by:

$$\omega = F^T * \gamma - \tau^T * \gamma; \qquad (11)$$

Substituting (9) into (8) we obtain:

$$\omega = (F^T * J - \tau^T)\gamma; \qquad (12)$$

Since the generalized q is independent, we have the equality

$$\tau = J(q)^T * F; \qquad (13)$$

From (11), we can write:

$$\begin{bmatrix}\tau_1\\ \tau_2\\ \tau_3\\ \tau_4\\ \tau_5\end{bmatrix} = \begin{bmatrix}J_1\\ J_2\\ J_3\\ J_4\\ J_5\end{bmatrix} * \begin{bmatrix}F_x\\ F_y\\ F_z\\ n_x\\ n_y\\ n_z\end{bmatrix}; \qquad (14)$$

By computing the mathematical model in MATLAB, we obtained the following results shown in figure 4. The results represent the behaviour of the joints, i.e. angles, velocity and acceleration, with reference to the motion of the human operator. This task was resolved using inverse kinematics with reference to the geometry given in figure 3.

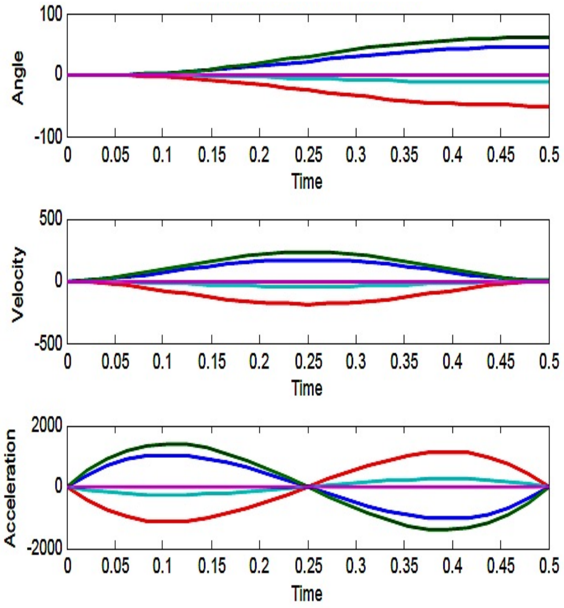

Figure 4. Robotic arm joints angles, velocities and accelerations with reference quantic polynomial trajectory

3.3 Discussion

By implementing the impedance control design using the obtained mathematical models in equations (3-6), we rearranged the system to focus on single input- single output. This permits evaluating whether the end effector is reaching the target area and applying the necessary force to execute the task. Therefore the simulation results as single input-single output presentation should highlight the position and the speed of movement of the end effector with reference to a desired position: tracking desired position will show the precision of the control system, while controlling the speed variation will generate enough power to gently execute the job.

Figure 5. represents the behaviour of the joints (thin blue curves) with reference to desired position (green line) according to the operator motion (red step signals).

From the results, it can be easily seen that the impedance controller has successfully driven the position of the end effector to the desired spot without overshooting. Taking into consideration that variable step signals are difficult to handle, the obtained results are satisfactory.

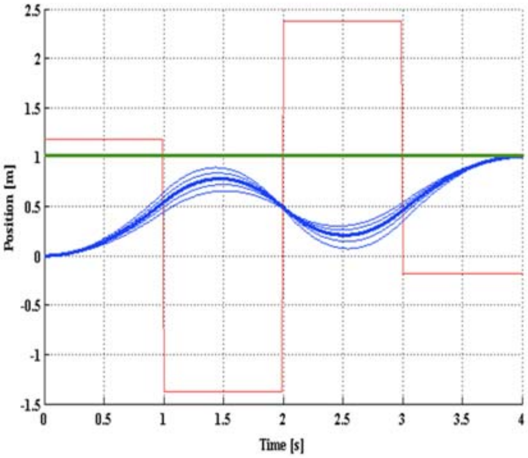

Figure 5. Position control of end effector using haptic impedance control method

Similarly, the control approach permitted to stabilize the velocity of the end effector without overshooting. This is a very important result. As was mentioned earlier impendace-type devices are very sensitive to motion. Hence any small variation in speed will generate more acceleration, which will produce more force. This will cause the end effector to exert more pressure on the structure being maintained. Figure 6. illustrates results of speed stabilization using hapric impedance control approach.

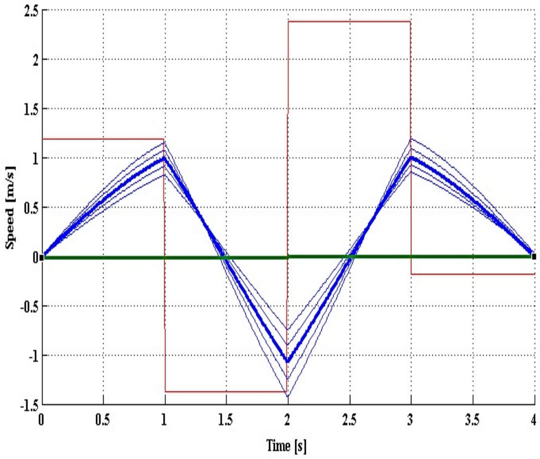

Figure 6. Speed control of end effector using haptic impedance control method

4 Future work

The global haptics financial studies indicate that the market actuator reached 2.7 billion dollars in 2015. It is also forecasted that the haptic market share can potentially reach 10.3 billion dollars with a growth rate of 37.3% annually [10].

With the new development in technologies, it is forcasted that haptics will reach new heights and be integrated in different intelligent products. Along with the wordwide tendency to build trusted fully autonomous robotic systems, telerobotics is still acquiring lots of researchers attention. This is due to the simplicity of the intelligent systems of the telerobotics in comparasion with the autonomous robots. One more attracting point that serves this field is the human ability to learn sometimes faster and percieve better than the machine. For instance, this is one of reasons why we didn't see until now fully autonomous surgical robot. Until having fully trusted autonomous systems, it is always good to have a human operator, as an observer or indirect executer for sensitive tasks. Telerobotics allows this option.

Referring to the presented paper here, we see room for improvement, especially when combining impedance and admittance haptic control into one algorithm. Although this was addressed by reseachers as hybrid haptics, the topic is not yet closed as the results are not close to perfection.Therefore, we dedicate our future work to study the hybrid approach, design intellectual control haptic system enabling to render small masses and generate better net force and accurate positioning of the end effector.

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