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Haptic interfaces for compensating dynamics of rescue walking robots

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Abstract

This paper presents a Neural Network approach to compensate dynamic terms, friction force in particular, of a rescue walking robot used in haptic interfaces. The impedance control through dynamic compensation of the friction force is studied, followed by the implementation of neural intelligent networks in the feed-forward loop in order to eliminate the corresponding terms in the dynamics, friction force in particular. The friction force model is analyzed using a general compensation method after which a trained Multi-Layer Neural Network is introduced in order to obtain an accurate friction model so that the movement of the walking robot feels free and unconstraint.

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Keywords: walking robot control, intelligent control methods, haptic interfaces, neural networks

1. Introduction

The dynamic elements play an important role for walking robots used in haptic interfaces and must be well defined in order to have an operation as natural and precise as possible, because the accuracy of such devices is very important. Thus, these dynamic parameters such as inertia, gravity and friction force should be adjusted so that user

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can feel a free and unconstraint motion. On the other hand, rescue robots represent a big challenge for the robotic research around the world because of the dangerous environments they are deployed in and the high uncertainty associated with these environments[1][2].

In order to adjust the dynamic parameters of rescue robots using haptic interfaces, several methods for dynamic compensation have been studied and developed such as compensation using different impedance in the control loop [3], friction learning and reduction using both a feed-forward compensator which takes into account the motor torque and angular speed to get the friction force, and a disturbance observer [4], friction compensation through Dahl method [5], utilizing a Moment Observer for unmodeled force determination and feed-forwarding to the actuation system in order to behave like a mass [6].

Intelligent control methods such as: fuzzy control, neural networks, neutrosophic method, etc. are good choice to achieve a more accurate compensation of all the above dynamic factors. One of this intelligent methods uses an Adaptive Fuzzy compensator, which has the capability to approximate any nonlinear function over the compact input space, has been adopted in this paper to compensate the friction, based on Lyapunov theory. Because of their compliance and extend application, we use neural networks to model and solve the dynamic drawbacks of the impedance haptic interfaces. Neural networks were developed for a large number of applications from decision making, pattern recognition to solving complex robotic problems. Being an important part of robotics, neural networks were also implemented in haptic devices for accurate control and compensation and estimation of dynamic elements like the contact force between the virtual environment and human operator [7], but also to get a much better stability through dynamic uncertainties approximation and a low execution time of the control loop [8].

The most common control diagram and the one which will be discussed in this paper is the impedance control, because of the compliant feature of impedance controllers and the possibility of using force feedback, while admittance control is used in applications which require large inertia.

A number of environmental factors can act on the manipulators, such as loads or other forces, their influence can hardly be anticipated. The action of such disturbances may be a cause of significant deviations from the reference motion of the rescue robot in relation to reference signals [9-12].

Haptic interfaces can be implemented in applications involving the use of a walking robot using force feedback from one or two of its legs end effector (on foot). These applications are useful when the robot is remotely operated of, the operator being able to receive tactile information, besides the video and audio as if on site. Walking robots controlled through haptic interfaces can be used in rescue operations, in case of natural disasters or in areas where access is difficult.

Further on the paper will discuss the impedance control through dynamic compensation of the friction force, followed by the implementation in the next chapter of neural intelligent networks in the feed-forward loop in order to eliminate the corresponding terms in the dynamics, friction force in particular.

In addition to the use of haptic interfaces, another great improvement is the implementing of the Virtual Projection Method [13, 14] with the advantage that combining audio-visual and haptic feedback substantially increase the safety of mobile robot teleoperation applications. For instance, safe control is essential for robotic operations in hazardous environments, search and rescue response, disposal of explosives and nuclear power plant maintenance or radioactive waste manipulation. Further, safe driving systems are important in many industrial applications such as freight handling or transportation.

2. Impedance control with compensation of dynamic parameters

In order to verify the impedance control with compensation of dynamic parameters, we took into account the representation of the rescue robot leg described in Fig.1, the direct kinematics for the position of the tool tip being carried out in space coordinates.

The control approach for a haptic interaction is very important because user movements must feel free and unrestricted, so when there is an interaction with an object, the human operator must perceive the exact force or interaction.

This is the reason why dynamic terms must be compensated, a rescue robot which doesn’t solve the dynamic problems has stability issues because of the high inertia and environment stiffness, due to actuator saturation and resonant modes, and position signal sampling.

Fig.1. The rescue robot leg.

In addition to that, in order to reduce dynamics influence feed-forward loops will be introduce to minimize or to cancel out the friction force (stiction and Coulomb) and gravity, an example of such control diagram being shown in Fig. 2.

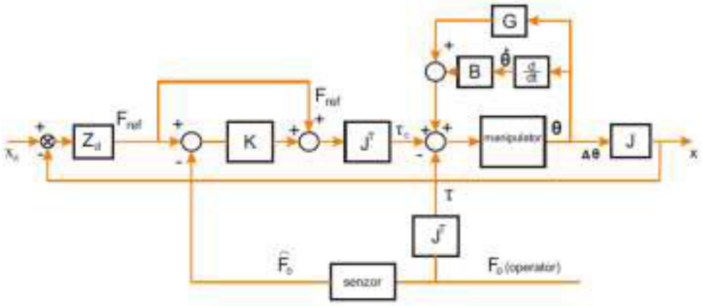

Fig.2. Compensation of dynamic terms.

In order to compensate robot's leg dynamic an accurate model for stiffness, damping and inertia is needed. In addition, because the friction cannot be compensated when there is no change in the force and motion, and because noise signal amplification can become a problem due to the compensation model, stability problems can occur. In the control diagram the linearized dynamics of the robot is represented. Cartesian positions of the haptic interface and joint position of the haptic mechanism are related by the Jacobian.

An impedance controller with force feedback is shown. It may be noted that in this block diagram there is a way for the sensed signal to reach at the haptic device. The force feedback is used to close the loop for the desired force generated by the controller.

A general model for friction force which uses a continuous function of a dead-zone torque is presented in equation (1) and latter introduced in the control diagram.

$$
\begin{aligned}
&\text{If } |\dot{\theta}| < v, \\
&\qquad f_f = \begin{cases} \Delta\tau & ; |\Delta\tau| < T_s \\ \mathrm{sgn}(\Delta\tau)\cdot T_c & ; |\Delta\tau| > T_s \end{cases} \\
&\text{If } |\dot{\theta}| \geq v, \\
&\qquad f_f = \mathrm{sgn}(\dot{\theta})\cdot T_c
\end{aligned}
\tag{1}
$$

where Ts, represents the stiction torque, Tc, Coulomb torque, and Δτ is the dead-zone torque obtained by subtracting user torque from reference torque.Also a model developed in Matlab which takes into account eq. (1) was used for friction calculation (Fig. 3) [15].

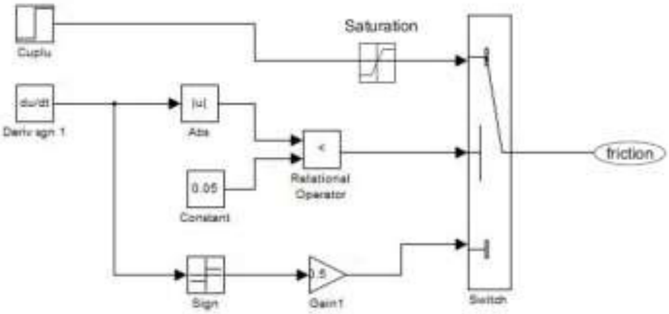

Fig 3. Matlab model of the friction force.

In order to calculate position x, from Fig. 2, we consider end-effector of the tool tip, the impedance of the haptic environment and the dynamics of the manipulator which is introduced by:

$$M(q)\cdot\ddot{q}+C(q,\dot{q})\cdot\dot{q}+G(q)+J^{T}(q)\cdot F+\overline{f}(t)=\Delta\tau \tag{2}$$

where M is the natural inertia matrix, C is the matrix which includes the Coriolis and centrifug terms, B is viscous damping matrix, G is the gravity vector, J is the system Jacobian, f is the vector of applied forces from human operator to end-effector where operator interacts with the device, and Δτ is the applied torque. The following relationship is obtain from the control diagram, where position is dependent the system dynamics and applied torques

$$x=J^{j}\cdot Z_{h}^{-1}\cdot\left(\tau_{c}-J^{T}\cdot F_{o}\right) \tag{3}$$

Compensating dynamics from this equation with a feed-forward term we can determine a more accurate position of the close loop control

$$x=J^{j}\cdot Z_{h}^{-1}\cdot(\Delta\tau_{fwd}+J^{T}\cdot F_{ref}-J^{T}\cdot F_{o}) \tag{4}$$

This feed-forward torque $\Delta\tau_{fwd}$ will be used in both eq.(1) for friction determination, in force from user determination and inertia as well.

In order to simulate the dynamic control of the haptic device, we have used Matlab Simulink for both cases, with and without dynamic compensation. For dynamic compensation case we were able to determine the friction force using velocity signals and torque signals (Fig.4). Applying this impedance, leads to finding the F_d forces from which we subtract the forces which are derived from the generator that simulates the response of the virtual environment.

A K_F amplification is applied for this difference, which can lead to a open loop system if the gain value is set to zero.After the amplification of the force error, we then add the calculated force from the positioning error. Then we multiply by the haptic leg Jacobian. This transfer function will require as input, along with the forces for which the transposed Jacobian matrix is applied, the angles a1 and a2 for the actual calculation of this matrix.

In order to avoid singularities given by the transposed Jacobian applied for this type of manipulator, we introduced a block diagram which was programmed such as the feedback to be calculated.

In the next step it's calculated the difference of torque, between the one given to the virtual environment and the one received from it, to be able to compensate the torque. Then, using the reverse transposed Jacobian matrix, the end-effector position is calculated to be returned in the closed loop.

3.Compensation using neural networks

Among different network structures, the multilayer perceptron NN (MLPNN) architecture has been employed for our purpose, as these networks are most frequently used for function approximation [10, 12, 14]. Networks are trained in this work using a back-propagation technique with neuron weights iteratively adjusted to minimize the error between the network output and the training set desired output (Fig. 5).

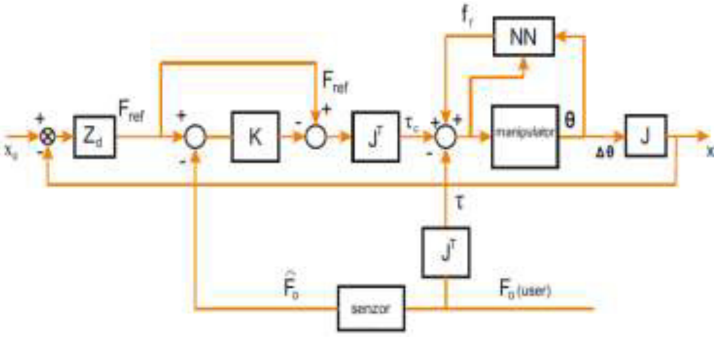

Fig.4. Compensating the friction term using Neural Networks

This training method can be implemented with the MATLAB Neural Network Toolbox using the TRAINLM function. The challenging part of using NNs is determining the design parameters(Fig. 6).

There is no specific recipe for the number of hidden layers, the number of hidden neurons or even which type of activation function to use.

Controller takes the position deviation difference between desired and actual position deviation of the haptic interface, and multiply by the desired impedance of the environment in order to generate a force F_{ref}.

This force is compared with the amplification of the difference between its value and force operator measured value, after which is transformed into torque using the transpose matrix J_T. By closing the control loop a decrease of inertia due to the force from human operator is desired, resulting a compensation of it. Further on the obtained torque is compared with the one from user, yielding a torque which will be used to determine the rotation of the motors, and to calculate the dynamic terms of the manipulator including friction force.

The rotation θ, will be introduce together with torque motor in the Neural Network control block and the friction force will be determined by training in accordance with the condition applied in the Neural Network algorithm.

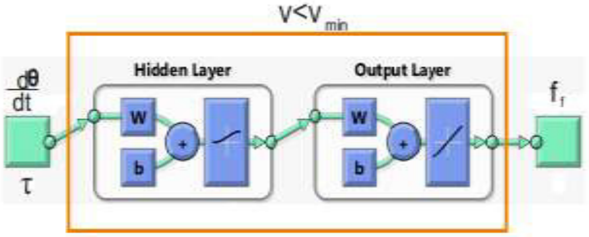

Fig.5. Trainnig the network for friction determination.

This Neural Network will be created taking into account two inputs, the number of nodes and layers, and the number of epochs needed in order to obtain the network output, the friction force in our case (Fig. 7). After these configurations, the network will enter the training phase, and after validation, it will perform the determination of the friction force.

4. Results and conclusions

By introducing haptics in walking robot control, the environment in which robot is moving can be better perceived by a remote operator, decisions can be made in real time depending on the audio-video but also tactile information received from sensors located on the robot.

Fig. 6 shows the amplitude of the force feedback from the leg's end-effector in case of an interaction with an object from the environment when the friction is not compensated. The force is mapped considering the position of the tool tip and the impedance of the environment in that point.

The results in both figures show the force feedback sent to the haptic device, according to impedance control function, when the rescue robot leg is in contact with an object in the environment.

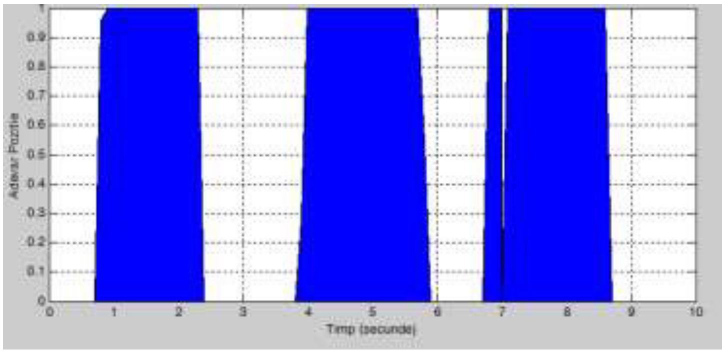

Fig.6 Position compensation when applying force in virtual environment.

The most relevant aspect occurs when a reaction force is received on the haptic device from the virtual environment. At that moment you can see in the Fig. 6 and 7 how the control law controls the position of the manipulator, the end-effector's force which acts upon the virtual environment, so that it can reach its reference position, as given by the human operator.

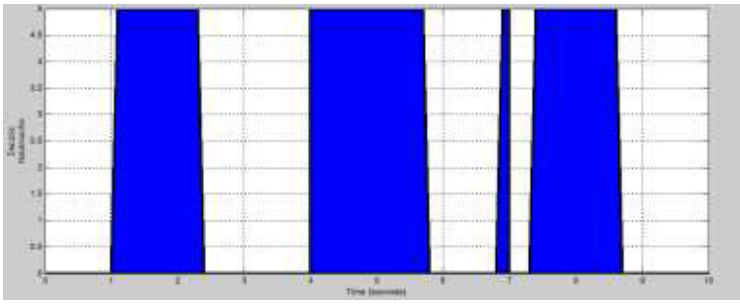

Fig.7. Position compensation in virtual environment.

Both simulations (Fig.6 and Fig.7) are made in Matlab Simulink using the Simulink model dynamic control with force compensation from Fig. 6 and show the variation of the force over time in relation with the position of the rescue robot leg in haptic. In case of compensating the friction with Neural Networks the force sent from the rescue robot leg to the haptic device is smaller when compared to the force which is not compensated following a better sense of touch of the environment the robot is moving.

The Neural Network method is one of the important control methods that can be used in order to compensate the dynamic influences. The new intelligent control methods such as Neutrosophic, Extenics etc. can be used in order to achieve a better sense of reality.

This control diagram allows the simulation of several impedance control methods, without the need for a virtual or physical model, for which it can be seen how effective the proposed control laws are.

Such compensated models can be used with much better performance in various applications rescue operations, in case of natural disasters or in areas where human access is difficult.

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