Pick to Place Trajectories in Human Arm Training Environment

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Abstract— **A new method of trajectory planning in rehabilitation robotics is presented. First were measured in healthy subject the pick to place trajectories while haptic robot was in zero impedance space. B-spline approximation is used to mathematically define the measured paths. This trajectory path serves as a central line for the rounding haptic tunnel. In addition to radial elastic and damping force an optional guidance force can be applied along the tunnel to reach the place point. Finally are presented the pick to place movements with and without tunnel use in stroke hemiplegic patient.**

Keywords— **trajectory planning, haptic interface, rehabilitation robotics.**

I. INTRODUCTION

The demographic structure of population in developed countries shows an increasing number of older people [1]. Among them the stroke is a leading cause of disability [2], to a large extent affecting the activities of daily living [3]. A numbers of controlled trials showed that enhanced physical therapy improves recovery after a stroke [4]. This fact confirms a growing necessity of rehabilitation approaches. In rehabilitation robotics the haptic interfaces combined with virtual reality largely improve the patient's motivation [5].

Several systems have been developed for robotic training of upper and lower extremities. Training systems for upper extremities are divided into two groups: end effectors and exoskeletons [6]. End effector upper extremity devices are more common. MIT-MANUS [7] with SCARA configuration, the MIME [8] system, which uses a Puma 560 robot manipulator, the Gentle/G [9] system based on the Gentle/S rehabilitation robot HapticMASTER, and the robot system for upper limbs rehabilitation developed by Deneve et al. [10] all belong to the class of end-effector based robots.

Human arm movement from point to point is important movement primitive in robotic rehabilitation. Different studies showed the rules that characterize measured human movement [11, 12, 13]. These rules are used as a natural movement bound.

This paper proposes trajectory shape planning using B-splines. The movements measured in healthy subjects are used for trajectory approximation with B-splines [15]. These are used in our case among others for new haptic object, a trajectory tunnel, which enables movement from pick to place point along a desired trajectory in a virtual haptic environment. The trajectory tunnel is developed as an independent haptic primitive in virtual tasks. Subject's arm is placed in a fixture on the end effector of the haptic robot HapticMaster that is used as a force measurement and position generation device.

II. METHODS

A. Haptic system specification

The rehabilitation system used in the study consists of the haptic interface device HapticMaster (Moog FCS Inc.), a wrist connection mechanism, a grasping device, a lower and upper arm gravity compensation mechanism, a 3D visualization system and a Dolby surround sound display. The robot and the grasping device are shown in Fig. 1.

Two subjects participated in the study. The first subject is a right handed, 24 years old healthy male. This participant had no history of neuromuscular or musculoskeletal disorders related to the upper extremities. The second participant is a right-hemiparetic subject, 40 years old female. Both subjects gave their informed consent to participate.

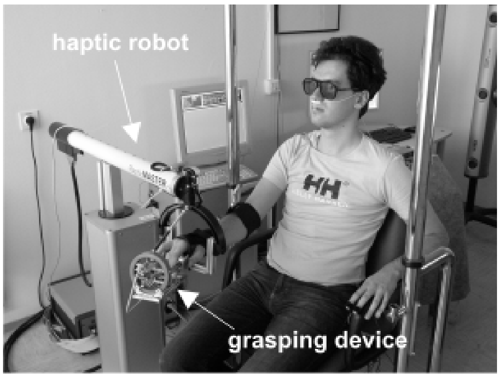

Figure 1: Subject training with haptic system: a grasping device is attached to the HapticMaster end-effector, a 3D projection screen is positioned in front of the subject.

B. Trajectory planning

Pick to place human movement from point to point in 3D space, including pick, transfer and release of the objects is

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of outmost priority in everyday life. Studies of the movements measured indicate several rules:

1. The path of the arm is curved from pick to place points and slightly deviates from a straight line. Slight curvature does occur, depending on the area of the arm's workspace [11, 14].
2. The velocity profile is bell-shaped. Human chooses the trajectory with the minimum jerk change of the hand. The acceleration profile of the movement contains no discontinuities [11].
3. The accuracy of the movement is inversely proportioned to the movement velocity. The relationship is known as Fitts' law [12].
4. The path is the most curved, where the velocity is the least [14].

Movements of the arm are becoming smoother and more elegant with exercise and learning. The smoothness of the movements is described [11] using the time derivative of the trajectory.

C. Realization of the pick to place trajectory using B-splines

For the trajectory path measurement was developed a simple task which included a block object on the floor and a table. The healthy subject had to pick the object and place it on the table. After successful placing, the object reappeared at a random starting point on the virtual floor. The movements were made in zero impedance robot mode. This set of the measured movements represents a reference pick to place trajectories.

On the basis of measured reference path trajectory, is generated a mathematically determined path trajectory combined with B-splines, which are used for local approximation and later interpolation of the measured movements with lower degree polynomials. The splines are used as basic functions which are smooth at contact points between segments. Contact points are also known as knots (Fig. 2).

Let $x_0 < x_1 < ... < x_n$ represent the knots. $b_{i,l}$ marks the i basic spline with l degree on the knots $\{x_j\}_{j=0}^{n}$. Choosing knots $x_{-l} < x_{-l+1} < ... < x_0$ and $x_n < x_{n+1} < ... < x_{n+l}$, a set can be defined:

$$b_{j,0}(x) = \begin{cases} 1, x \in [x_j, x_{j+1}) \\ 0, \quad otherwise \end{cases} \tag{1}$$

$$b_{j,k}(x) = \frac{x - x_j}{x_{j+k} - x_j} b_{j,k-1}(x) + \frac{x_{j+k+1} - x}{x_{j+k+1} - x_{j+1}} b_{j+1,k-1}(x) . \tag{2}$$

The defined set $\{b_{j,k}(x)\}$ is the base of the splines vector space with knots $x_0,...,x_n$ and degree k. The whole function $s(x)$ is sum of functions

$$s(x) = \sum_{j=0}^{n-k-1} d_j b_{j,k}(x) \qquad x \in [x_k, x_{n-k}], \tag{3}$$

where d_j are control points and function $s(x)$ in valid on the interval $[x_k, x_{n-k}]$.

The control points are coefficients of the approximation with basic functions. DeBoor's algorithm [15] is suitable and simple for calculating the function $s(x)$. DeBoor's algorithm enables fast calculation and is numerically stable. Different number of control points can be used to describe the path of the arm from pick point to place point, depending on the complexity of the trajectory. Fig. 2 shows five basic functions when the trajectory is defined by five control points. An example of a healthy person measured movement and its corresponding approximation interpolated with B-splines are shown on Fig. 3.

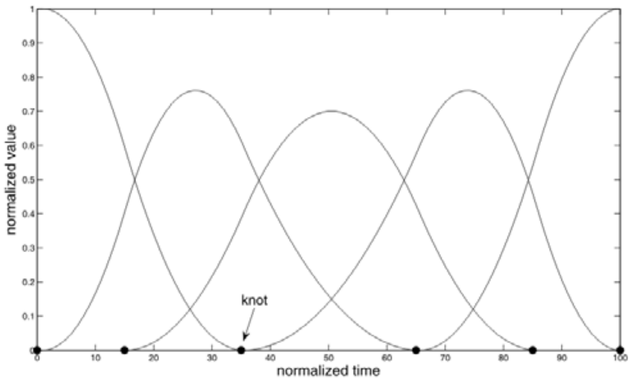

Figure 2: Five basic functions generated with B-splines.

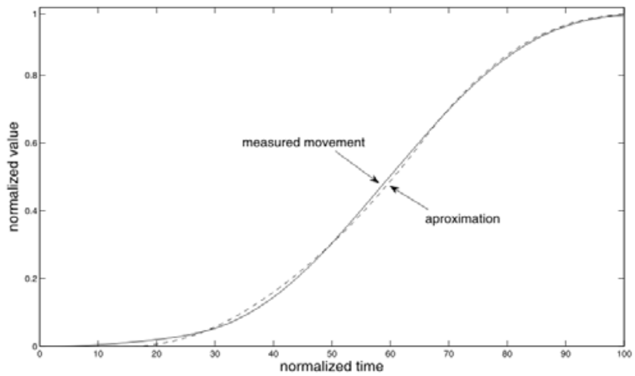

Figure 3: Measured movement and an approximation of arm movement.

D. The haptic trajectory tunnel

The approximated path using B-splines defines central curve line of the trajectory tunnel, linking the pick point and place point. This haptic trajectory tunnel also has the radius along the central curve line. The end point of the robot is haptically presented as a ball. The position of the ball is defined with the position of the robot end point while the size of the ball is minimal. The user can move the ball along the tunnel, as well as in radial direction when the ball diameter is smaller than the diameter of the tunnel. The collision between the object and the tunnel wall is modeled as a spring-damper system with a stiffness and viscous friction. The guidance force along tunnel central line could also be provided with a reference time value that defines the movement duration.

The described model of the haptic trajectory tunnel is designed as an object in the haptic Matlab/Simulink environment. Haptic tunnel is designed to be used as an independent haptic primitive.

III. Results

To show that the human movements are repeatable and that the curvature of the movement depends on the direction and length of the pick to place point movement, we observed differences between the measured points and the linear path between pick and place points. From there were calculated average values of control points and then taken their absolute value for movement in a horizontal plane. These absolute values are differences of the measured control points values and the straight line control points values. The movements were performed by healthy subject in different directions. Fig. 4 shows the absolute values of the middle three control points (d_2, d_3, d_4) for different pick points in the xy plane. The solid black color marks value of the second control point, the grey dotted color marks value of the fourth control point while the white block marks the value of the third control point. The place point of the trajectory was always in the center of the coordinate system. The absolute values of the control points are depicted at pick points in four directions. The second and fourth control point are divided into two parts, showing values in x and y direction respectively. The width of the white block represents the value of the third control point in x direction while the block height represents the value in y direction.

Fig. 5 shows trajectories of movement from pick to place point in zero impedance space. The trajectories were measured in hemiparetic subject performing six pick to place movements and the Fig. 6 shows the trajectories with the haptic trajectory tunnel present.

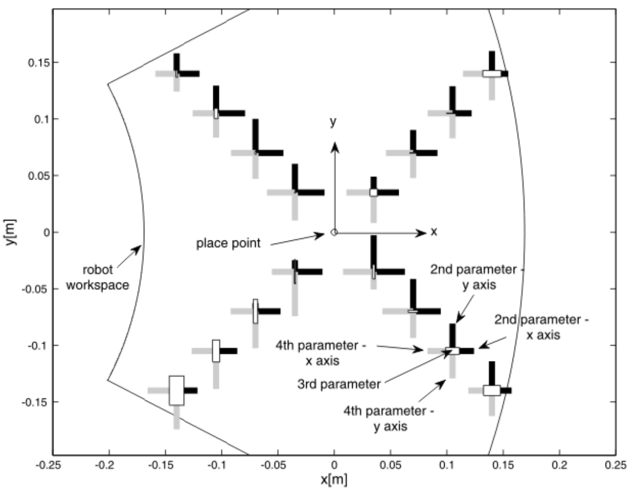

Figure 4: Values of second, third and fourth control point (d_2, d_3, d_4) for movements in the xy plane for different movements in man arm workspace.

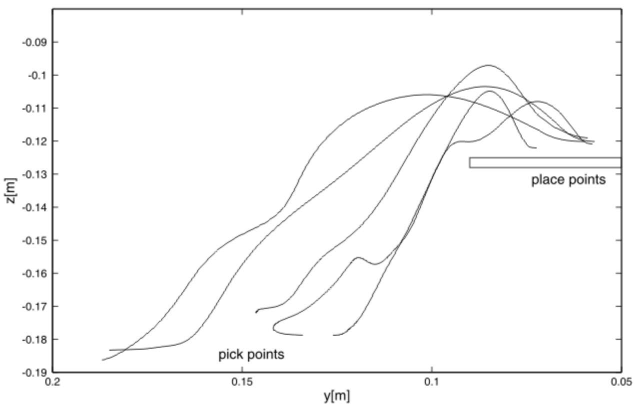

Figure 5: Pick to place movements of the hemiparetic subject in the pick and place task in zero impedance space.

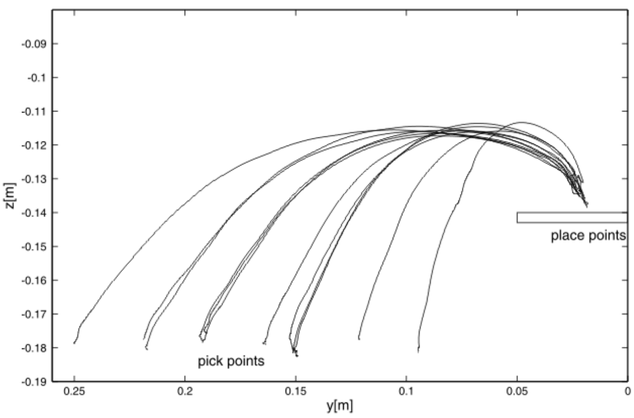

Figure 6: Pick to place movements of the hemiparetic subject in the pick and place task with the haptic trajectory tunnel present.

IV. DISCUSSION

To confirm that the human movements are repeatable, were initially examined the average absolute values of the middle three control points only by taking a number of measurements. Fig. 4 shows that in the same directions values of the control points stay in the same proportion while the values decrease proportional with the length of the movements in all directions. These measurement findings confirmed that for similar pick and place points human movements are repeatable. It can be recognized from Fig. 5 and Fig. 6 that the haptic trajectory tunnel determines the trajectory of the movement from the pick to the place point for a hemiparetic subject. Therefore, with the haptic trajectory tunnel, the patient is guided in cooperative manner to make same pick to place movements as healthy person with only minimal intervention from haptic system.

The big advantage of the presented trajectory planning method is primarily in the fact that the complexity of the movement being approximated does not play an important note. By using more control points, the method could be implemented also for other, much more complex trajectory planning problems, not only the point to point and pick to place movement.

V. CONCLUSIONS

The goal of this study was to create a trajectory planning algorithm and to develop adequate haptic object. The algorithm exploits use of the movements measured in healthy people as a base for further trajectory planning in patients. The results showed that the control points values of the approximated movements stay in the same proportion in the same directions while the values decrease proportional with the length of the movements in all directions. The measurement findings confirmed that for similar pick and place points human movements are repeatable. Further, a haptic object which helps the patient to move along the minimum intervention trajectory was designed. The results of our simple task confirmed that the patient can make same pick to place movements as healthy person when using the trajectory tunnel. These findings show that our model, which uses B-splines and haptic tunnel together with other movement primitives, can be easily implemented in rehabilitation robotics. Our next step is inclusion of the tunnel in an upper extremity robotic therapy system.

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