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Trajectory Planning of a One Degree of Freedom Assistive Robotic Knee

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Abstract- **The invention of Hybrid Assistive (HAL) Limb was chosen as one of the important inventions for the mankind. Hybrid Assistive Limb is mainly of two types. HAL controlled by bio electrical signals sensed from the human body and HAL operated by external microcontroller based electrical devices. This thesis mainly concentrates for the development of the latter. These types of devices possess operating easiness and assistance to physically handicapped people. These devices are less complex in operation and cheaper than the former. The use of passive devices may cause inconveniences in daily routines and difficulties in mobility for the user. Current robotics orthotic devices have advantages over passive devices because it is capable of aiding the knee and reducing the knee stress without affecting the mobility of the user. The objective of this work is to study and develop a portable active orthotic device that can be used for rehabilitative purposes. The 3D model of the proposed assistive mechanism has been created. This structure is then analysed. Trajectory planning of the knee joint by considering human walking pattern is also done. The position velocity and acceleration of the joint with respect to time has been plotted using MATLAB and the results obtained are discussed.**

Keywords- **Trajectory Planning, Assistive knee, Walking support system, One DoF Joint, Lower extremity.**

I. INTRODUCTION

The knee joint is the most problematic joint. In 2003, about 19.4 million visits where made to physician's office in relation to knee problems in United States. Treatments of knee injuries and diseases will require proper resting of the knee and reducing the pressure acting on the knee joint. Reducing pressure at the knee joint helps to relief the strain and stress acting on the knee. In the present work, the use of a robotic device is to assist the knee joint, thereby reducing the pressure acting on the knee joint.

Many institutions around the globe have carried out research and development on exoskeletons and assistive devices to empower or aid the human limbs. Some of them are AKROD V2, ROBOKNEE, HAL 5, BLEEX, LOCOMAT etc. [1-3]

AKROD V2 is the active knee rehabilitation device developed by North-eastern University. It contains electro rheological fluid on one side of its structure such that it can turn solid in less than a milli second with the application of a voltage. This would provide resistance to motion on a healing joint and it aims to help the muscle regain strength

Fig: 1.1 AKROD V2

ROBOKNEE is the first prototype of a powered knee device developed by yobotics. It is aimed at helping people with weak lower extremity muscle and muscle disease to walk and climb stairs more easily. The purpose of the RoboKnee was to demonstrate that super-human capabilities can be achieved by a powered orthotic device while not significantly interfering with normal activities. The RoboKnee provides a power assist while walking up stairs and while doing knee bends. While not super impressive, the RoboKnee did provide for super-human capabilities by allowing the user to perform deep knee bends almost indefinitely.

Fig: 1.2 ROBOKNEE

HAL, or Hybrid Assistive Limb, is a powered exoskeleton suit currently in development by Tsukuba University of Japan. There are currently two prototypes, HAL 3 which has bulkier servo-motors and only has the leg function, and HAL 5, which is a full-body exoskeleton for arms, legs, and torso. HAL 5 is currently capable of allowing the operator to lift and carry about five times as much weight as he or she could lift and carry unaided. It operates by sensing weak electrical impulses from muscles via electrodes on the operator's skin and sending them to the onboard computer which in turn analyzes them and activates corresponding servos of the suit, mimicking the wearer's motions. The whole suit is powered by a 100-volt battery attached to the operator's waist.

Fig: 1.3 Hybrid Assistive Limb-5

II. OBJECTIVE

The objective of the present work is therefore to come up with a robotic device for a patient with knee problem. The preliminary work is aimed to test the basic concepts behind the proposed active orthotic device. This is likely to be a potentially useful research area due to the rising numbers of sports related injuries and increase in aging world population. As this work is closely related to robotics, it is required to do trajectory planning of the knee joint by considering human walking pattern. The goal of trajectory planning is to describe the requisite motion of the manipulator as a time sequence of joint locations and the derivatives of locations which are generated by interpolating or approximating the desired path by a polynomial function.

III. FORCES ACTING ON THE KNEE AND THE FORE LEG

The anatomical system for the knee and the foreleg is as follows.

Proximal segment	: Femur (thigh bone)
Distal segment	: Tibia (shin bone) & fibula
Joint	: knee

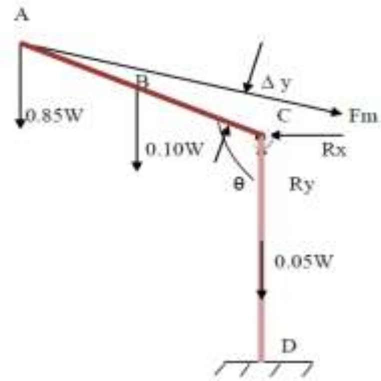

Fig: 3.1 The forces acting on the knee joint and the lower extremity

The forces acting on the human knee joint is shown as line diagram. 85% of the total weight of the person is acting on the hip joint which is denoted as point A. The reaction forces Rx & Ry are acting on the knee joint. The muscle force is acting away from the knee at an angle Δy which is denoted as Fm. Θ is the angle between proximal segment and the distal segment. In the case of the assistive device, the muscle force component is zero and hence the reaction forces will be minimum.

IV. TRAJECTORY PLANNING

The end-effector of a manipulator is required to move in a particular fashion to accomplish a specific task. The execution of the specific task requires the manipulator to follow a pre planned path, which is the larger problem of motion or trajectory planning and motion control for the manipulator. The goal of trajectory planning is to describe the requisite motion of the manipulator as a time sequence of joint locations and the derivatives of locations which are generated by interpolating or approximating the desired path by a polynomial function. Trajectory planning involves certain terms and it is important to understand their meaning without ambiguity, to avoid confusion between terms.

Fig: 4.1 CAD model of the proposed Walking Support system

A set of cubic polynomials can be used for the interpolation of trajectory, preserving the continuity in the first and second derivatives at the interpolation points [10]. Such cubic polynomials are known as cubic spline functions. The cubic spline trajectories are the most preferred among the interpolating functions as the cubic polynomial is the lowest degree polynomial for which both first and second derivative exist, allowing for continuity in velocity and acceleration, and it is computationally more efficient.

q^s = starting point value

q^g = goal point value

t_g = travel time or time to reach the goal

To describe the joint motion, assume that the cubic polynomial is,

$$q(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$$

The first derivative of this equation will give the parabolic velocity profile equation

$$\dot{q}(t) = a_1 + 2a_2 t + 3a_3 t^2$$

The second derivative of the first equation will give the linear acceleration equation

$$\ddot{q} = 2a_2 + 6a_3 t$$

For a smooth motion between the initial and goal points, the functions $\dot{q}(t)$ & $q(t)$ have to be smooth. This requirement imposes two constraints each on the joint position and velocity functions. Further, $q(t)$ is zero for t<0 and t>t_g. This along with the continuity requirements gives the four constraints as,

$q(0) = q^s$
$q(t_g) = q^g$
$\dot{q}(0) = 0$
$\dot{q}(t_g) = 0$

Applying these constraints in the main equation, the four unknowns can be calculated.

$$a_0 = q^s$$

$a_0 + a_1 t + a_2 t^2 + a_3 t^3 = q^g$
$a_1 = 0$
$a_1 + 2a_2 t + 3a_3 t^2 = 0$

After solving these four equations, coefficients of cubic polynomial can be obtained as follows,

$a_0 = q^s$

$$a_1 = 0$$

$a_3 = \frac{3}{t_g^2}(q^g - q^s)$

$a_3 = \frac{-2}{t_g^3}(q^g - q^s)$

Thus the cubic polynomial to interpolate the path connecting the initial joint position to the final position is [8]

$$q(t) = q^s + \frac{3}{t_g^2}(q^g - q^s)\, t^2 - \frac{2}{t_g^3}(q^g - q^s)\, t^3$$

V. Results & Discussion

The aim is to determine the time history of the position, velocity and acceleration of the end effectors of a one degree of freedom knee joint which moves from start to goal point via two intermediate points. The desired end effector motion is specified in the table. It is assumed as a cubic spline trajectory in each segment and the continuity of velocity at the via points is enforced.

Table 5.1: Desired end effector motion

End Effector	Path points			
	1	2	3	4
Position (rad)	0	0.2617	0.7853	1.0471
Velocity (rad/s)	0	0.5235	0.2618	0
Time (s)	0	1	2	1

The given trajectory has two via points and, therefore, will have three segments and three cubic polynomials will be required to define the time history of motion of end effector. Let the three cubic polynomials be,

$P_1(t) = a_1 + b_1 t + c_1 t^2 + d_1 t^3$
$P_2(t) = a_2 + b_2 t + c_2 t^2 + d_2 t^3$
$P_3(t) = a_3 + b_3 t + c_3 t^2 + d_3 t^3$

Applying boundary conditions to the above equations,

$P_1(0) = 0$
$P_1(1) = 0.2617$
$\dot{P}_1(0) = 0$
$\dot{P}_1(1) = 0.5235$

The four coefficient for the first segment polynomial P_1 are computed from the above equations and the results obtained are,

$a_1 = 0$
$b_1 = 0$
c_1 =0.2616
d_1 =0.0001

And the cubic for the first segment is,

$P_1(t) = 0.2616t^2 + 0.0001t^3$
$\dot{P}_1(t) = 0.5232t + 0.0003t^2$
$\ddot{P}_1(t) = 0.5232 + 0.0006t$

Similarly the boundary conditions for the second cubic is given by,

$P_2(1) = 0.2617$
$P_2(3) = 0.7853$

$\dot{P}_2(1) = 0.5235$
$\dot{P}_2(3) = 0.2618$

The four coefficient for the second segment polynomial P_2 are computed from the above equations and the results obtained are

$a_2 = -0.5889$
$b_2 = 1.2431$
$c_2 = -0.4579$
$d_2 = 0.0654$

And the cubic for the second segment is

$P_2(t) = -0.5889 + 1.2431t - 0.4579t^2 + 0.0654t^3$
$\dot{P}_2(t) = 1.2431 - 0.9158t + 0.1962t^2$
$\ddot{P}_2(t) = -0.9158 + 0.3924t$

Similarly the boundary conditions for the third cubic is given by,

$P_3(3) = 0.7853$
$P_3(4) = 1.0471$
$\dot{P}_3(3) = 0.2618$
$\dot{P}_3(4) = 0$

The four coefficient for the third segment polynomial P_3 are computed from the above equations and the results obtained are,

$a_3 = 9.424$
$b_3 = -8.3776$
$c_3 = 2.618$
$d_3 = -0.2617$

And the cubic for the third segment is

$P_3(t) = 9.424 - 8.3776t + 2.618t^2 - 0.2617t^3$
$\dot{P}_3(t) = -8.3776 + 5.236t - 0.7851t^2$
$\ddot{P}_3(t) = 5.236 - 1.5702t$

The cubic polynomials P1, P2, P3for the three segments of the point to point trajectory are obtained. These cubic polynomials describing the position of the end effectors are plotted using MATLAB. Their first and second derivative, which represents velocity and acceleration of the end effectors, respectively are plotted below.

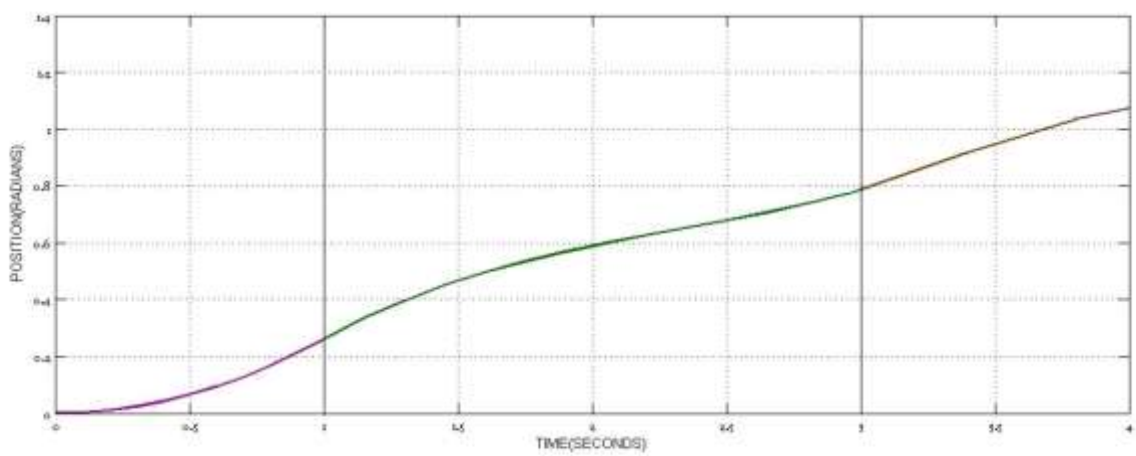

Fig: 5.1 Time history of position for the cubic polynomial

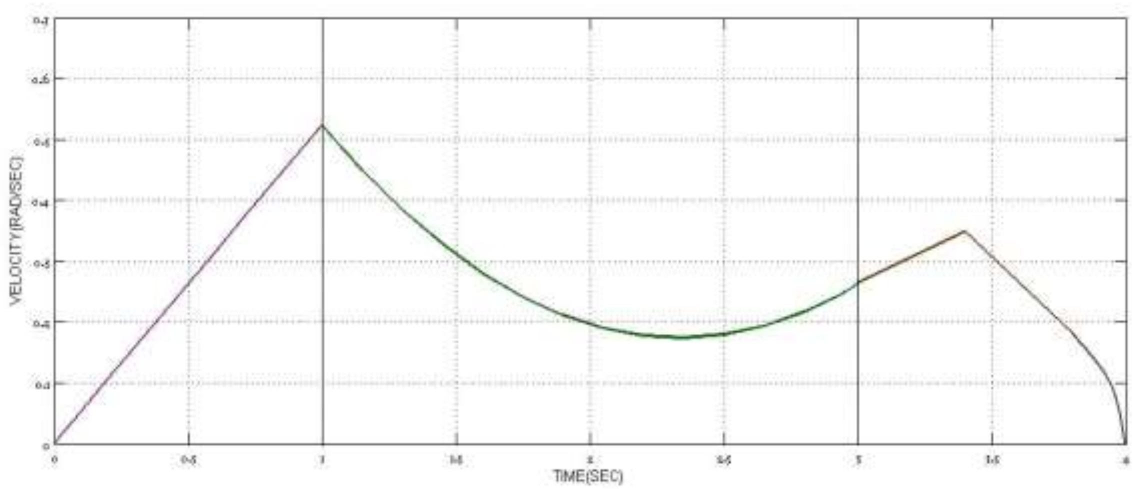

Fig: 5.2 Time history of velocity for the cubic polynomial

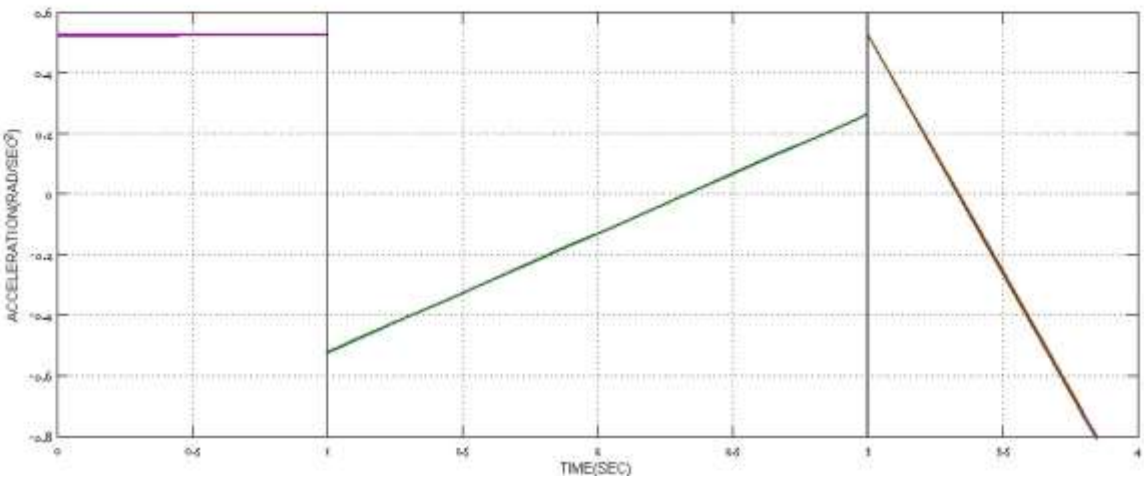

Fig: 5.3 Time history of acceleration for the cubic polynomial

From these plots, it is easy to observe that the continuity of position and velocity is maintained and the acceleration is still discontinuous. The first graph is obtained by plotting the third degree (cubic) equation and hence the plots obtained are non linear and continuous. The time taken for the manipulator to move the whole path is taken as 4 seconds and that path is connected with two via points.

The first derivative of the cubic will give the velocity and it is plotted. It is observed that for the first path, the velocity plot obtained is almost straight line. This is due to the minimum value for the coefficient of second degree term in the equations. This can be eliminated by selecting the higher degree polynomial for defining the path. The acceleration plot obtained is linear and discontinuous. This can be eliminated by selecting a forth degree polynomial for defining the trajectory. The initial velocity and the final velocity are taken as zero. The velocity at any point in between the initial and the final point can be obtained from the plots.

V. CONCLUSION

An assistive knee with DC stepper motor is developed. Based on the working condition of knee joint, the motor can function as a brake or an accelerator. In this paper, the knee joint with only one DOF is considered, and future work can be done by increasing the number of degrees of freedom by considering the hip joint and the ankle joint. Three cases were discussed in this work and the results obtained are satisfactory. The time history of the position, velocity and acceleration of the end effector of a one degree of freedom knee joint has been plotted using MATLAB and the plot obtained is satisfactory.

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