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Motion Planning for a High-speed Manipulator with Mechanical Joint Stops based on Target Dynamics and PCH System

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Abstract—**This paper reports a motion planning scheme for a high performance robot aiming to realize the motion control skills exhibited by professional golfers. The robot has a dexterous mechanism with similar distribution of actuators' capability and a pair of mechanical joint stops like human beings. The proposed motion planning method combines target dynamics together with port-controlled Hamiltonian (PCH) system theory resulting in an energy controller which not only takes the mechanical joint stops into account but also realizes torque compensation from a high-power actuator to a low-power actuator. Simulation and experimental results prove the proposed method can generate the golf swings with specified hitting speed and finish position for our specially designed robot.**

I. Introduction

DURING the past several years, more and more attention has been paid to the research on high-speed manipulators. H. Asada and M. Vukobratovich *et al.* adopted high performance actuators to improve manipulators' running speed [1-2]. F. Pierot *et al* proposed a high-speed HEXA robot using parallel mechanism [3].

Gymnastic robots capable of performing high-speed dynamic sports motions were also avidly proposed by many researchers. To the best of our knowledge, P. L. Andersson first successfully developed a ping-pong playing robot which was capable of beating many humans [4]. A. Ming and M. Kajitani studied the human dynamic skill in high-speed actions and extended the motion control skill in human golf swings to a golf swing robot [5-6]. S. Suzuki and H. Inooka investigated a similar golf swing robot that could adjust its motion to both specified values of swing velocity and specific characteristics of individual golf clubs [7]. Their robot had a passive wrist joint and could utilize the coupling force generated by its swing motion and shaft vibration like professional golfers [8-9]. In [10], S. Suzuki, S. J. Haake, and B. W. Heller proposed a multiple modulation torque planning method for the robot which considered the effect of whole body motion and a naturally delayed wrist turn to improve swing efficiency. Y. Hoshino, Y. Kobayashi, and G. Yamada discussed the vibration control problem of their golf swing robot and proposed an optimal control scheme using a state observer that considered disturbance to suppress the vibration [11]. Y. Inoue and K. Shibata's group proved that a properly "timed" wrist action with consideration of the golf ball position could improve the horizontal club head speed at impact [12]. They also proposed an impedance control strategy for their golf swing robot to emulate different-arm-mass golfers [13]. However, most of these golf swing robot researchers took their interests in building a robot to evaluate performance of golf clubs/balls and, in general, adopted predefined joint torque patterns in motion control which leads to low robot dynamic performance.

With different starting point of research, the authors have received inspirations from human body structure and motion control skills exhibited by professional golfers and have been attempting to realize high-speed dynamic manipulation by a dexterous robot using human-like mechanism design and unique control methods [5-6]. To validate this inspiration, a new two-link golf swing robot has been developed by the authors. This robot has a high-power actuator in its shoulder joint, a very light and low-power actuator and a pair of mechanical joint stops in its wrist joint to imitate the dexterous upper limb structure of the human body (Fig. 1). A unique motion controller then is required to drive such human-like mechanism to perform high-speed dynamic manipulation by utilizing torque/power transfer from the shoulder joint to the wrist joint, just like that in human beings. Unfortunately, the motion control methods adopted in [7-13] and proposed in [14-18] are not consistent with our goal because they need pre-defined torque or angle trajectories. The existing results on underactuated systems [19] are also not suitable for our fully actuated robot. Due to the highly nonlinear nature of the robot dynamics, using numerical method to plan the high-speed dynamic manipulation subject to the torque limitation of the wrist joint is very difficult and the computational cost is very high. These restrictions promote us to investigate a new motion controller for our robot.

In our previous works, we have proposed a target dynamics [20] based motion planner for the golf swing robot [21], but joint stops are not taken into account. In [22] we reported another planner based on proportional plus gravity and coupling torque compensation (PGCTC) and reverse time symmetry, but this method is only suitable for offline planning.

In the present paper, we propose a target dynamics and port-controlled Hamiltonian (PCH) [23] system based motion planning method for golf swings, which takes the joint stop into account and has the potential of realizing real-time control.

The remainder of this paper is organized as follows. The robot's mechanism and model and the problem statement are

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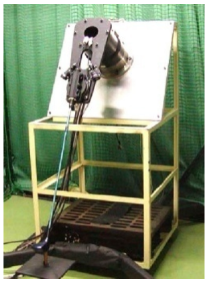

Fig. 1 Prototype of the golf swing robot

introduced in section II. Motion planning method is discussed in section III. Simulation and experimental results are given in section IV. A conclusion and future work are given in the final section.

II. Problem Formulation

A. Robot Mechanism

Fig. 1 is a picture of the developed robot. The robot consists of a base frame, joint 1 (shoulder joint), an arm, joint 2 (wrist joint), a pair of joint stops, and a club. Joint 1 is to realize the function equivalent to the shoulder in human and is driven by a high-power DD motor. In joint 2, a pair of joint stops and a light and low-power DD motor whose load capability is only a little bigger than the static torque due to the weight of the club are used to realize the function of the wrist in human.

B. Mechanical Joint Stop

A pair of mechanical joint stops is mounted on the wrist joint. Fig. 2 shows the detailed structure of them. Each joint stop consists of a module with a magnet and a shock absorber fixed on the arm and another magnet mounted on the rotating part of the gripper of the wrist joint. The elastic force is derived from the repelling force between two magnets, and the viscous force is generated by the absorber to buffer the impact of the rotating magnet to the magnet of the fixed module.

C. Mathematical Model

Fig. 3 shows the mathematical model of the robot. Considering the golf swing robot as a rigid-body system, its dynamics can be represented by the following equation:

$$\boldsymbol{\tau} = \mathbf{M}\ddot{\boldsymbol{\theta}} + \mathbf{N}\left(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}\right) \tag{1}$$

Where, $\boldsymbol{\tau} = [\tau_1, \tau_2 + \tau_{st}]^T$ is the generalized joint torque, τ_1 and τ_2 are the output torques of the DD motors, τ_{st} is the passive

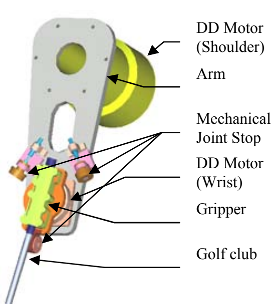

Fig. 2 Mechanical joint stop

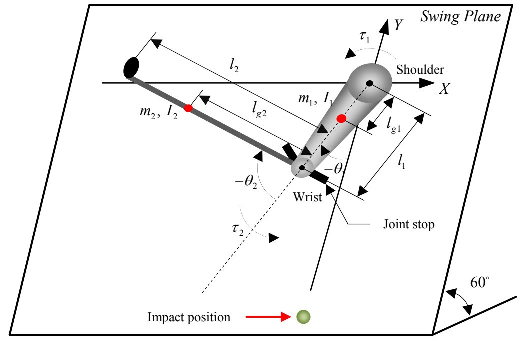

Fig. 3 Model of the Golf swing robot

torque generated by the joint stops, $\boldsymbol{\theta} = [\theta_1, \theta_2]^T$ is the generalized coordinate, $\mathbf{M}$ is the inertia matrix, $\mathbf{N}\left(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}\right) = [N_1, N_2]^T$ is the term due to Coriolis force, centrifugal force, gravity, and frictional/damping force (Fig. 3). The rotation range of the shoulder joint is $-190^\circ \le \theta_1 \le 210^\circ$ and the free rotation range of the wrist joint is $-120^\circ \le \theta_2 \le 120^\circ$ (the wrist joint will come into contact with the joint stops outside this range in both clockwise and counterclockwise directions).

Due to the wrist actuator selection criterion given above, the maximum output torque of the wrist joint is strictly limited and is only 10Nm. The maximum output torque of the shoulder joint is 100Nm.

The torque-angle characteristic of the joint stops is represented by the following equation:

$$\begin{aligned} \tau_{st} &= b_0\left(1 - \exp\left(-b_1\theta_s\right)\right) \\ \theta_s &= \frac{\theta_2 - \theta_{st\lim}}{\sigma} \end{aligned} \tag{2}$$

Where, θ_s represents the normalized angular displacement of the joint stops with respect to their starting position $\theta_{st\lim}$. σ, b_0, and b_1 are constant parameters. In the clockwise direction, the joint stop constant parameters are $\theta_{st\lim} = -120^\circ$, $b_0 = -0.002708$, $b_1 = 1.904$ and in the counterclockwise direction they are $\theta_{st\lim} = 120^\circ$, $b_0 = 0.001315$, $b_1 = -2.035$.

D. Problem Statement

Generally speaking, the golf swing can be divided into three phases: backswing, downswing, and follow-through. From the robotics point of view, we distinguish two variants of the whole swing. The first is the hitting problem which arises from backswing and downswing. Since the robot starts the swing from the address position at rest and achieves the specified hitting speed at the impact position, not only energy must be added into the system in a suitable fashion, but also the impact position must be controlled accurately. The second is the stopping problem that arises from follow-through. After hitting a ball, kinetic energy must be removed from the system in a suitable fashion so that both the club and the arm slow down before coming to a stop at the specified finish position.

Hereafter we propose an energy controller based on both target dynamics and port-controlled Hamiltonian (PCH) system to solve the above problems.

III. Motion Planning Method

PCH system based energy control and target dynamics based method have been adopted by some researchers to deal with motion control problems. In this study we combine them together to deal with the golf swing planning problem with consideration of joint stops.

A. PCH System Based Energy Control

The dynamics of the golf swing robot can be expressed in an equivalent PCH system. Hence there is an energy control law to drive the system to achieve a desired energy level [23]:

$$\boldsymbol{\tau} = \begin{bmatrix} -K_H\bar{H}\dot{\theta}_1 + K_H\bar{H}\dot{\theta}_2 \\ K_H\bar{H}\dot{\theta}_1 - K_H\bar{H}\dot{\theta}_2 \end{bmatrix} \tag{3}$$

Where, $\bar{H} = H - H_d$, H is the Hamiltonian function, namely the mechanical energy of the system, H_d is the desired mechanical energy level, K_H is the parameter.

However, no joint stop is taken into account in the control law (3). Which means only PCH based energy control cannot plan the golf swings for our robot and another control law is required to deal with this problem.

B. Target Dynamics Based Energy Control

Essentially speaking, target dynamics is one of the I/O linearization methods. This method provides a way of reducing the motion control task in complex high-DOF space to the one in simple low DOF-target sub-space.

Therefore, we may adopt RP coordinates to describe the two-link golf swing robot which is generally described by RR coordinates and map it to a one-DOF system. Fig. 4 shows the coordinate transform.

In Fig. 4, l is the length of the pseudo link from the base (shoulder joint) to the club head, and θ is the angle of the pseudo link about Y direction. We select θ and its derivate $\dot{\theta}$ as the outputs of the system and rewrite the dynamics of the golf swing robot in state space representation:

$$\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x},\boldsymbol{\tau}) = \begin{bmatrix} \dot{\theta}_1 & \dot{\theta}_2 & \mathbf{M}^{-1}\left(-\mathbf{N}(\mathbf{x}) + \boldsymbol{\tau}\right) \end{bmatrix}^T \tag{4}$$

Where, $\mathbf{x} = \left[\theta_1, \theta_2, \dot{\theta}_1, \dot{\theta}_2\right]^T$ is the state variable, the output function is defined as

$$y = \mathbf{Y}(\mathbf{x}) = \begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \theta_1 + \alpha \\ \dot{\theta}_1 + \dfrac{l_1(l_2 + l_1\cos\theta_2)}{l_1^2 + l_2^2 + 2l_1l_2\cos\theta_2}\dot{\theta}_2 \end{bmatrix} \tag{5}$$

With consideration of the necessity of pumping energy into the system to realize desired hitting speed, we adopt a harmonic oscillator governed by an energy control law (6)

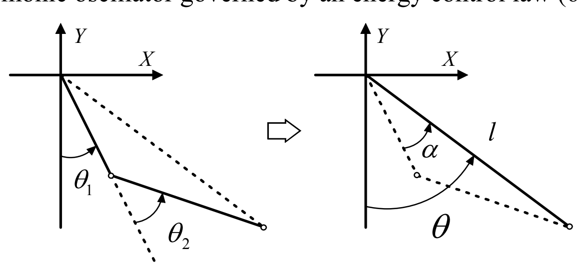

Fig. 4 Coordinate transform

$$\dot{y} = \begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix}' = \begin{bmatrix} 0 & 1 \\ -\omega^2 & -K_e\left(E - E^*\right) \end{bmatrix} \begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix} \tag{6}$$

as the target dynamics of the output function. Where, K_e is a positive constant, E is the pseudo energy of the target dynamics and is defined as

$$E = \dot{\theta}^2/2 + \omega^2\theta^2/2 \tag{7}$$

and E^* is the desired pseudo energy level.

According to (5), we have

$$\dot{\theta} = \dot{\theta}_1 + \frac{l_1(l_2 + l_1\cos\theta_2)}{l_1^2 + l_2^2 + 2l_1l_2\cos\theta_2}\dot{\theta}_2 = \dot{\theta}_1 + \frac{l_1}{l_2 + l_1}\dot{\theta}_2 \tag{8}$$

Then the hitting speed is derived according to (7-8):

$$\dot{\theta} = v_x/(l_1 + l_2) \tag{9}$$

The desired pseudo energy level corresponding to the hitting speed v_x at the impact position is:

$$E^* = E_i^* = \dot{\theta}^2/2 = v_x^2/2(l_1 + l_2)^2 \tag{10}$$

Equation (10) indicates that the pseudo energy is uniquely determined by the hitting speed at the impact position. Hence the specified hitting speed can be achieved by controlling the energy level of the robot.

According to (4-7) and the target dynamics method [21], the control law is derived as follows:

$$a_1\tau_1 + a_2(\tau_2 + \tau_{st}) = -\omega^2\theta - K_e\left(E - E_i^*\right)\dot{\theta} + a_1N_1 + a_2N_2 + a_3 \tag{11}$$

Where,

$$a_1 = \left(n_{11} + \frac{l_2(l_2 + l_1\cos\theta_2)}{l_1^2 + l_2^2 + 2l_1l_2\cos\theta_2}n_{21}\right),\ a_3 = \frac{\left(l_1^2 - l_2^2\right)l_1l_2\dot{\theta}_2^2\sin\theta_2}{\left(l_1^2 + l_2^2 + 2l_1l_2\cos\theta_2\right)^2},$$

$$a_2 = \left(n_{12} + \frac{l_2(l_2 + l_1\cos\theta_2)}{l_1^2 + l_2^2 + 2l_1l_2\cos\theta_2}n_{22}\right),\ \begin{bmatrix} n_{11} & n_{12} \\ n_{21} & n_{22} \end{bmatrix} = \mathbf{M}^{-1}$$

C. Full Swing Planning Considering Joint Stop

Based on the above-mentioned theoretical analysis, full swing motion planner can be obtained by taking the elastic potential energy generated by the joint stops into account in E and selecting appropriate target energy level for the hitting speed and the finish position. Hereafter we discuss the motion planning methods for the hitting problem and the stopping problem respectively.

1) Motion planning for hitting problem

Because the golf club will be in contact with the joint stops to utilized its passive torque in the swing, the elastic potential energy E_{st} generated by the joint stops must be added into E. According to (2), E_{st} is defined as follows.

In clockwise direction:

$$E_{st} = \int_{-\theta_{st}}^{0} \tau_{st}d\theta_{st} = b_0\theta_s - \frac{b_0}{b_1}\exp(b_0\theta_s) + \frac{b_0}{b_1} \tag{12}$$

In counterclockwise direction:

$$E_{st} = \int_{0}^{\theta_{st}} \tau_{st}d\theta_{st} = b_0\theta_s + \frac{b_0}{b_1}\exp(b_0\theta_s) - \frac{b_0}{b_1} \tag{13}$$

Hence, the total pseudo energy should be modified to be:

$$E = \dot{\theta}^2/2 + \omega^2\theta^2/2 + E_{st} \tag{14}$$

In addition, according to the definition of Hamiltonian function, $H = E$ holds. Considering the gravity item and selecting the first equation of (3) as the input torque of the shoulder joint, we have the following pre-impact controller:

$$\begin{cases} \tau_1 = -K_H\left(E - E_i^*\right)\left(\dot{\theta}_1 - \dot{\theta}_2\right) + \partial\left(E - E_i^*\right)/\partial\theta_1 \\ \tau_2 = \left(-\omega^2\theta - K_e\left(E - E_i^*\right)\dot{\theta} + a_1N_1 + a_2N_2 + a_3 - a_1\tau_1\right)/a_2 - \tau_{st} \end{cases} \quad (15)$$

2) Motion planning for stopping problem

The golf swing robot will not stop at the specified finish position using the control law (15) because of the incorrect target energy level and target dynamics. We modify the target dynamics (6) to be the following form:

$$\dot{y} = \begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix}' = \begin{bmatrix} 0 & 1 \\ -\omega^2 & -K_{ef}\left(E - E_f^*\right) \end{bmatrix} \begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix} - \begin{bmatrix} 0 \\ -\omega^2\theta_f \end{bmatrix} \quad (16)$$

Where, θ_f is the desired finish position, $E_f^* = 0.5\theta_f^2$ is the pseudo potential energy level at the finish position. The system governed by (16) will slow down and stop at θ_f, which means the resulting control law will also slow down and stop the robot at θ_f after it passes through the impact position. Herein θ is adopted as the control switch trigger: if $\theta < 0$, the robot is controlled by (15), otherwise, the control law discussed in this subsection is applied. To avoid instability resulting from the sudden change of the desired energy level from E_i^* before the impact to E_f^* after the impact and the sudden introduction of the finish position θ_f, we adopt a continuous polynomial function smoothly connecting $v_x^2/2(l_1 + l_2)^2$ and $0.5\theta_f^2$ instead of a constant $E_f^* = 0.5\theta_f^2$ as the desired energy level:

$$E_f^* = \begin{cases} \dfrac{v_x^2}{2(l_1 + l_2)^2} - a\theta^3 - b\theta^2 - c\theta, & \left(0 \le \theta < \theta_f\right) \\ 0.5\theta_f^2, & \left(\theta = \theta_f\right) \end{cases} \quad (17)$$

where a, b, c are subject to: $\dfrac{v_x^2}{2(l_1 + l_2)^2} - a\theta_f^3 - b\theta_f^2 - c\theta_f = \dfrac{1}{2}\theta_f^2$

and adopt a continuous function $\theta_f\left(1 - e^{-q\theta}\right)$ increasing from zero instead of a constant θ_f as the desired finish position. Then we get the following target dynamics:

$$\dot{y} = \begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix}' = \begin{bmatrix} 0 & 1 \\ -\omega^2 & -K_{ef}\left(E - E_f^*\right) \end{bmatrix} \begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix} - \begin{bmatrix} 0 \\ -\omega^2\theta_f\left(1 - e^{-q\theta}\right) \end{bmatrix} \quad (18)$$

and the implicit control law is:

$$\begin{aligned} a_1\tau_1 + a_2\left(\tau_2 + \tau_{st}\right) = {} & -\omega^2\left(\theta - \theta_f\left(1 - e^{-q\theta}\right)\right) - K_{ef}\left(E - E_f^*\right)\dot{\theta} \\ & + a_1N_1 + a_2N_2 + a_3 \end{aligned} \quad (19)$$

Again, adopting the first equation of (3) as the input torque of the shoulder join we get the following post-impact control law:

$$\begin{cases} \tau_1 = -K_{Hf}\left(E - E_f^*\right)\left(\dot{\theta}_1 - \dot{\theta}_2\right) + \partial\left(E - E_f^*\right)/\partial\theta_1 \\ \tau_2 = \left(-\omega^2\left(\theta - \theta_f\left(1 - e^{-q\theta}\right)\right) - K_{ef}\left(E - E_f^*\right)\dot{\theta}\right)/a_2 \\ \qquad + \left(a_1N_1 + a_2N_2 + a_3 - a_1\tau_1\right)/a_2 - \tau_{st} \end{cases} \quad (20)$$

D. Torque Compensation

Because of the dexterous structure of the robot, the maximum output of the actuator in the wrist joint is very small ($|\tau_2| \le \tau_{2\max} = 10\text{Nm}$). Hence when the active torque τ_2 obtained from (15, 20) exceeds its limitation, the exceeding part τ_{2over} should be compensated for to avoid instability. According to (11, 19), if $|\tau_2| > \tau_{2\max}$, let $\tau_2 = \text{sign}(\tau_2)\tau_{2\max} + \tau_{2over}$ and define the new input torques as τ_1', τ_2' after considering the torque limitation and the torque compensation, then we have:

$$a_1\tau_1 + a_2\tau_{2over} = a_1\tau_1' \quad (21)$$

Thus the new active torques become:

$$\begin{cases} \tau_1' = \tau_1 + a_2\tau_{2over}/a_1 \\ \tau_2' = \text{sign}(\tau_2)\tau_{2\max} \end{cases} \quad (22)$$

Where, τ_1 is calculated using (15) and (20).

E. Diagram of the Golf Swing Motion Planner

As a conclusion of this section, Fig. 5 shows the diagram of the proposed motion planner. The target energy is calculated according to (10) and (17) for the hitting problem and stopping problem respectively. The pseudo energy is determined by (14). The controller is governed by (22).

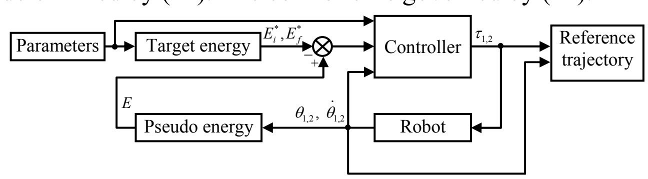

Fig. 5 Diagram of the proposed motion planner

IV. Simulation and Experiment

By using the pre-impact control law for the backswing and downswing and the post-impact control law for the follow-through, various golf swings fulfilling the desired hitting speed at the impact position and the desired finish position can be generated. As an example, the simulation and experimental results with a hitting speed of 27m/s is shown to verify the effect of the proposed method. The parameters are: $\omega = 5.18$, $K_e = 0.04$, $K_{ef} = 0.7604$, $K_H = -0.1448$, $K_{Hf} = 0.2327$, $\theta_f = 4.1061$, $q = 2.5$, $a = 0$, $b = 5.7847$, $c = 1.7611$.

A. Simulation

Figs. 6-11 show the simulation results.

Fig. 6 shows the active torque trajectories output by the DD motors. It can be seen the outputs of both motors reaches the maximum limitation in the downswing to make full use of their capabilities to accelerate the golf club.

Fig. 7 shows the passive torque history generated by the mechanical joint stops. It is easily to notice by comparing this figure with Fig. 8 that the peak passive torque in counterclockwise direction emerges in the beginning of downswing. This means the passive torque is utilized to accelerate the golf club. In addition, the minus passive torque shown in the follow-through is used to slow down and stop the club.

Fig. 8 shows the joint angle trajectories. From this figure we know the whole golf swing, including the backswing, downswing, and follow-through, is successfully generated by the planner.

Fig. 9 shows the angular velocities. It can be seen that in the follow-through, both the arm and the club are slowed down and finally stopped. Around the impact position, an interesting phenomenon is found: there is a concavity with the arm angular velocity. This is due to the utilization of dynamic coupling in the high-speed swing [6].

Fig. 10 shows the pseudo energy history which includes the elastic potential energy. The energy reaches the desired energy level corresponding to the hitting speed 27m/s at the impact position. In the first half of the follow-through, the energy tracks the desired energy level accurately. However, in the second half of the follow-through, the track error becomes a little bigger. We guess this is due to the unmodeled static friction force in the system because this phenomenon occurs in the low-speed swing.

Fig. 11 shows the elastic potential energy stored in the joint stops, which is corresponding to Fig. 7. The maximum energy is obtained when the passive torque reaches its peak.

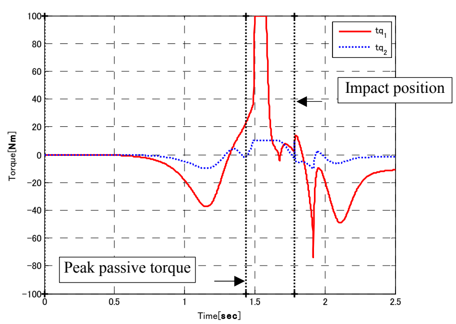

Fig.6 Input torques

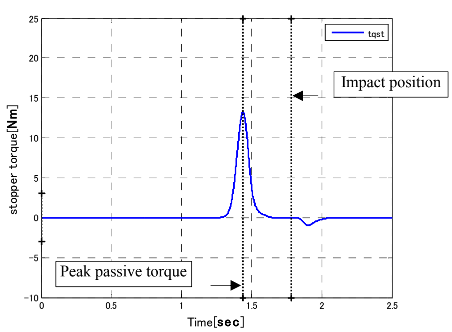

Fig.7 Passive torque by the joint stop

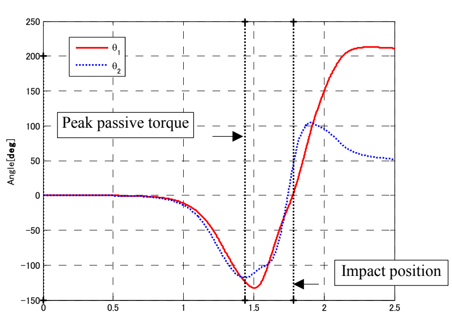

Fig.8 Joint angles

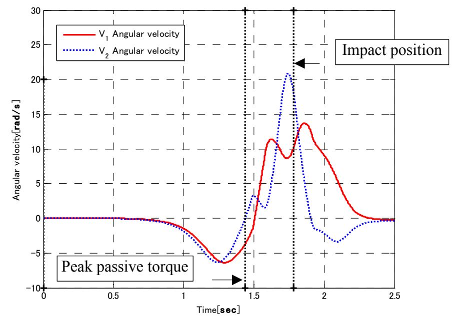

Fig. 9 Angular velocities

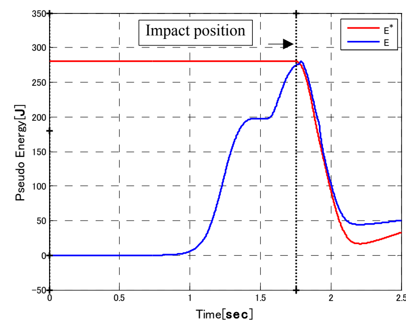

Fig.10 Energy

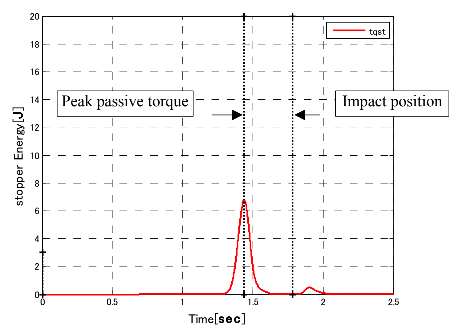

Fig. 11 Elastic potenial energy by the joint stops

B. Experiment

Experiments are carried out to evaluate the proposed motion planner. The control system of the real golf swing robot is shown in Fig. 12. The reference trajectories including the output torques of both DD motors, the angles and the angular velocities of the arm and the club are generated offline by the proposed motion planning method. These trajectories are input to the robot as the feedforward control signal, a PD controller is used to guarantee the global stability.

The simulation results obtained above is used in the experiment and the experimental results are shown in Figs. 13-15.

The results demonstrate the experiment is consistent with the simulation though there is deviation between the reference trajectories and the experimental ones.

From the above simulation and experimental results, we can come to a conclusion that the proposed motion planning method successfully generates desired golf swings for the golf swing robot with mechanical joint stops.

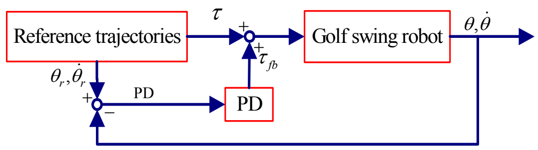

Fig.12 Control system of the real robot

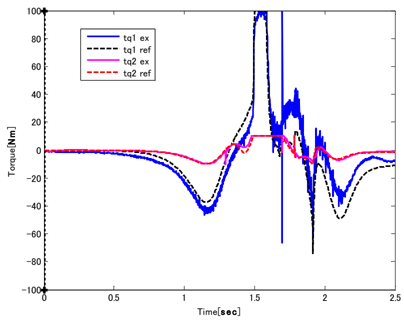

Fig.13 Input torques

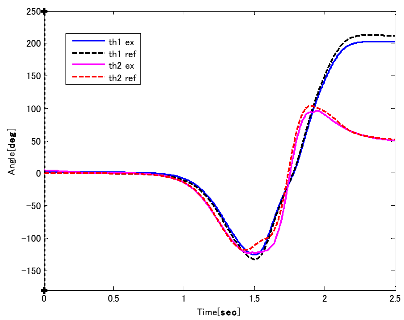

Fig.14 Joint angles

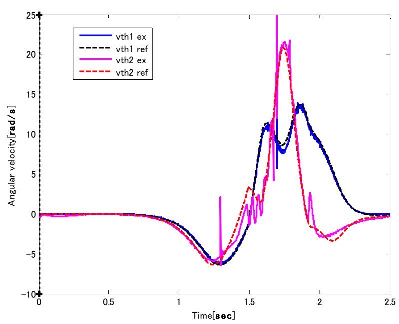

Fig.15Angular velocities

V. CONCLUSION

This paper reports our up-to-date results on the motion planning problem of a high-speed manipulator: a golf swing robot. An energy control scheme based on target dynamics and PCH system has been proposed by the authors.

This scheme combines target dynamics together with PCH system resulting in an energy controller, which can drive the robot to follow a swing trajectory with specified hitting speed at the impact position and specified finish position.

As compared with our previous work, the mechanical joint stop is taken into account and the resulting problem is solved successfully in the controller design.

The simulation and experimental results show the feasibility of the proposed method.

Finally, as future work we are aiming to apply the proposed controller directly to the robot to achieve real-time control. Results will be reported in our next paper.

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