Study On Golf Swing Robot

-Motion control method based on energy contol-

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Background

Motion control of hyper-dynamic manipulation

Capability of hyper-dynamic manipulation like humans'

Smart structure → *Motion control skill*

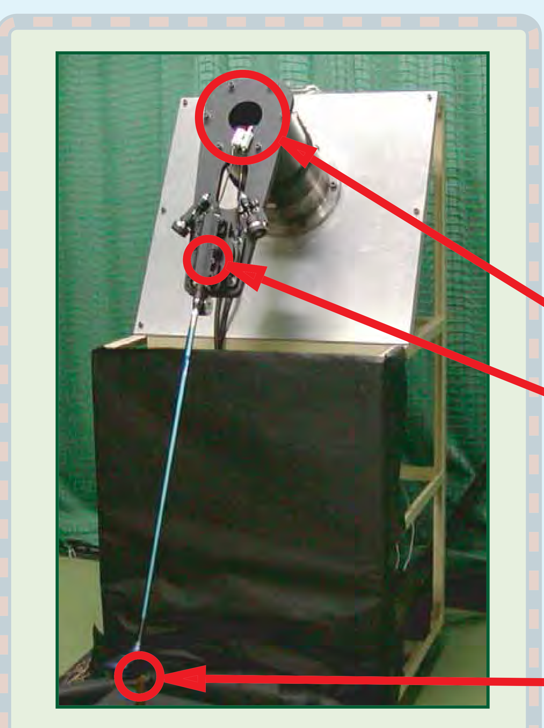
Offline motion generation + PD control

Optimization based mathmathical method

Problems:
1. Difficult to solve strong nonlinear problems
2. Difficult to converge to a global solution
3. High time cost of calculation

Research Object

2R Hyper Dynamic Manipulator Based on the Dynamically-Coupled Driving



State equation:

$$\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x},\boldsymbol{\tau}) = \begin{bmatrix} \dot\theta_1 \\ \dot\theta_2 \\ \mathbf{M}^{-1}(-\mathbf{N}(\mathbf{x})+\boldsymbol{\tau}) \end{bmatrix}$$

Smart structure → *Utilization of dynamically-coupled driving*

Driving torque limitation:
DD Motor1: *Maximum Torque 100 Nm*
DD Motor2: *Maximum Torque 11 Nm*

→ Smart Structure

Torque compensation of DD motor 2

Impact position: both the arm and the club are downward vertically in the swing plane

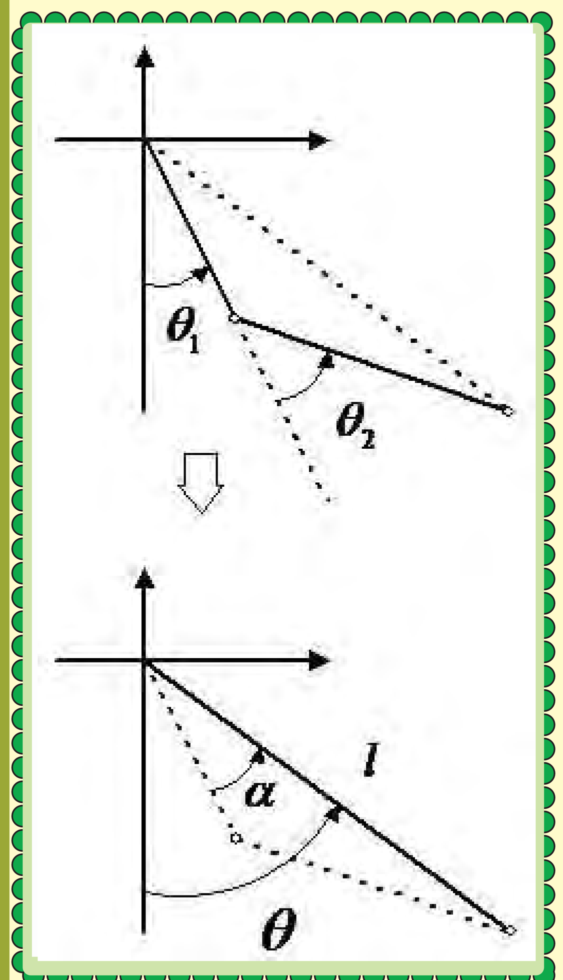
Realization of hyper dynamic manipulation while in a smart structure

Research Purpose

To establish a new control method to realize accurate control of high-speed golf swings with utilizing dynamically coupled driving:

* *Stable and high accurate control of golf swings*
* *Active torque compensation*

Target Dynamics Method



Assume a plant

$$\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x},\mathbf{u}),\ \mathbf{y} = \mathbf{H}(\mathbf{x},\mathbf{u})$$

is linearizable, We define the Lie derivative as

$$L_{\mathbf{F}}\mathbf{H} = \frac{\partial \mathbf{H}}{\partial \mathbf{x}} \cdot \mathbf{F}$$

Then, if

$$L_{\mathbf{F}}\mathbf{H} = \mathbf{w}$$

the system will follow the motion of the system

$$\dot{\mathbf{y}} = \mathbf{w}$$

in control of the following law:

$$\mathbf{u} = L_{\mathbf{F}}\mathbf{H}^{-1}(\mathbf{x},\dot{\mathbf{y}})$$

Pre-impact controller design

State equation:

$$\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x},\boldsymbol{\tau}) = \begin{bmatrix} \dot\theta_1 \\ \dot\theta_2 \\ \mathbf{M}^{-1}(-\mathbf{N}(\mathbf{x})+\boldsymbol{\tau}) \end{bmatrix}$$

Output function:

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

Target dynamics:
harmonic oscillator in control of energy law

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

$$E = \dot\theta^2/2 + \omega^2\theta^2/2$$

Control law:

$$a_1\tau_1 + a_2\tau_2 = -\omega^2\theta - K_e(E-E^*)\dot\theta + a_3 + a_1N_1 + a_2N_2$$

→

$$\tau_1 = K_h(E-E^*)(\dot\theta_1 - \dot\theta_2) \quad \textbf{(Port-controlled Hamilton system)}$$
$$\tau_2 = \left[\left(-\omega^2\theta - K_e(E-E^*)\dot\theta + a_3 + a_1N_1 + a_2N_2\right) - a_1\tau_1\right]/a_2$$

Active torque compensation of the wrist

$$\tau_2 = \tau_{2\max} + \tau_{2\Delta} > \tau_{2\max}:\ a_1\tau_1 + a_2\tau_2 = a_1\tau_1 + a_2(\tau_{2\max} + \tau_{2\Delta}) = a_1\left(\tau_1 + \frac{a_2}{a_1}\tau_{2\Delta}\right) + a_2\tau_{2\max}$$
$$\tau_2 = -\tau_{2\max} - \tau_{2\Delta} < -\tau_{2\max}:\ a_1\tau_1 + a_2\tau_2 = a_1\tau_1 + a_2(-\tau_{2\max} - \tau_{2\Delta}) = a_1\left(\tau_1 - \frac{a_2}{a_1}\tau_{2\Delta}\right) + a_2(-\tau_{2\max})$$

→

$$\tau_2 > \tau_{2\max}:\ \tau_1 = K_h(E-E^*)(\dot\theta_1 - \dot\theta_2) + a_2(\tau_2 - \tau_{2\max})/a_1,\quad \tau_2 = \tau_{2\max}$$
$$\tau_2 < -\tau_{2\max}:\ \tau_1 = K_h(E-E^*)(\dot\theta_1 - \dot\theta_2) + a_2(\tau_2 + \tau_{2\max})/a_1,\quad \tau_2 = -\tau_{2\max}$$

Post-impact controller design

Target dynamics:
Single pendulum in control of Proportional Plus Gravity Compensation (PPGC)

$$\dot{\mathbf{y}} = \begin{bmatrix} \theta \\ \dot\theta \end{bmatrix}' = \begin{bmatrix} 0 & 1 \\ -K_p & -K_i \end{bmatrix}\begin{bmatrix} \theta \\ \dot\theta \end{bmatrix} - \begin{bmatrix} 0 \\ -K_p\theta_f \end{bmatrix}$$

Control law of the pseudo angle:

$$a_1\tau_1 + a_2\tau_2 = -K_p(\theta - \theta_f) - K_i\dot\theta + c + a_1N_1 + a_2N_2$$

Control law of the arm:

$$\tau_1 - \tau_2 - c_1 = M_1\ddot\theta_1 + \Omega_1\sin\theta_1$$

where:

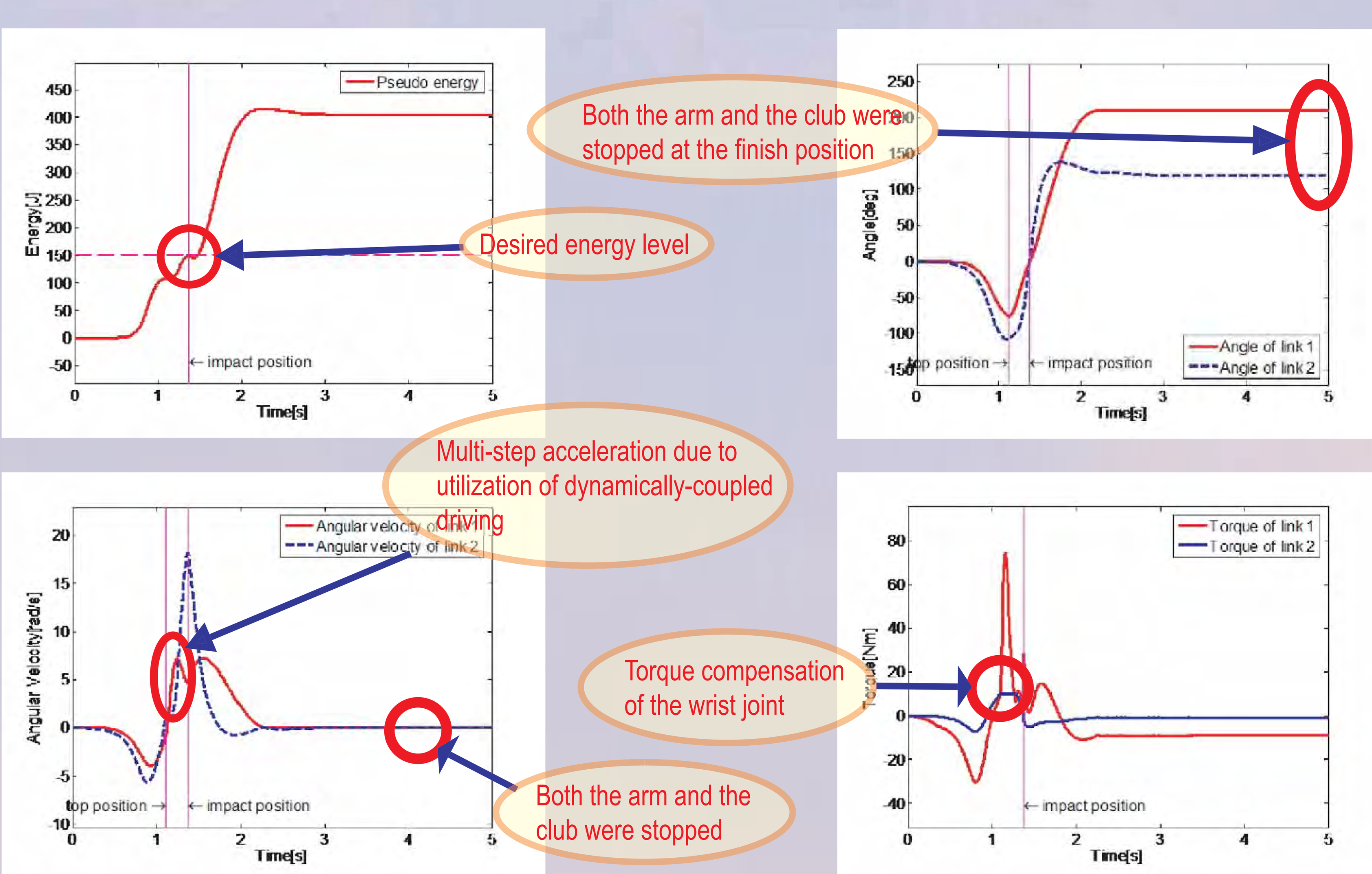
$$M_1 = (m_1l_{g1}^2 + m_2l_1^2 + J_1),\ \Omega_1 = (m_1g_yl_{g1} + m_2g_yl_1)$$
$$c_1 = m_2l_1l_{g2}\left[(\ddot\theta_1 + \ddot\theta_2)\cos\theta_2 - \sin\theta_2(\dot\theta_1 + \dot\theta_2)^2\right]$$

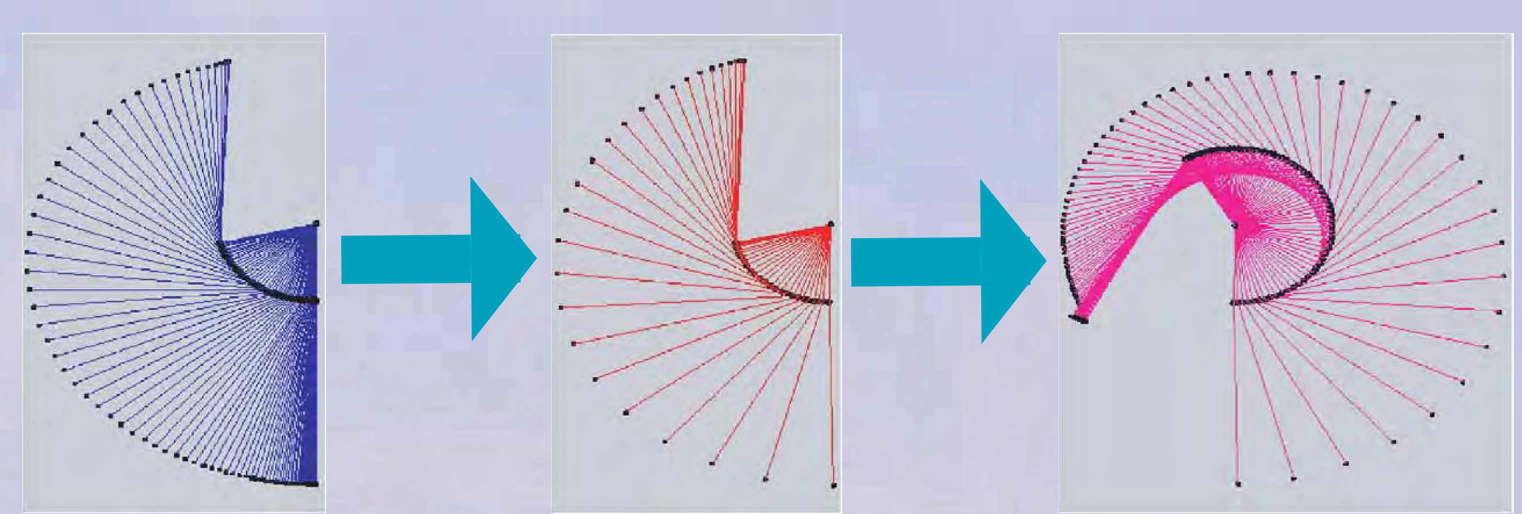
Control law:

$$\tau_1 = \left[-K_p(\theta-\theta_f) - K_i\dot\theta + c + (a_1N_1 + a_2N_2)\right]/(a_1+a_2) + a_2\left[c_1 + \Omega_1\sin\theta_1 - K_{i1}\dot\theta_1 - K_{p1}(\theta_1 - \theta_{1f})\right]/(a_1+a_2)$$
$$\tau_2 = \left[-K_p(\theta-\theta_f) - K_i\dot\theta + c + (a_1N_1 + a_2N_2)\right]/(a_1+a_2) - a_1\left[c_1 + \Omega_1\sin\theta_1 - K_{i1}\dot\theta_1 - K_{p1}(\theta_1 - \theta_{if})\right]/(a_1+a_2)$$

Results of Numerical Examples

Impact speed: *20m/s*
Impact position: *the angular positions of the arm and the club are 0 [deg]*





(a) backswing (b) downswing (c) follow-through

Energy control ***PPGC control***

Conclusion

A target dynamics based energy control law for pre-impact swing and proportional plus gravity compensation control law for post-impact swing has been proposed. Numerical results show:

* *Stable and high accurate control of golf swings*
* *Utilizaiton of dynamcally-coupled driving by active torque compensation*