UNIVERSITY OF CRAIOVA

Faculty of Automatics, Computers and Electronics

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PHD THESIS

(Abstract)

Control Algorithms for Balancing Pendulum Models with Elastic Components

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In this dissertation, author examines control algorithms for robots with elastic components. Two objects are concern is two-legged robot with elastic legs and elastic inverted pendulum. Their dynamic equations are generated and controllers are created to applied.

Firstly, mathematical model of kinds of inverted pendulum are presented. Based on these dynamic equations and some real experimental model in laboratories, simulation and experimental results under different kinds of controllers through kinds of inverted pendulum are generated. Conventional, nonlinear and intelligent controllers are tested in both simulation and experiment. Mainly, linear feedback are used as PD control and LQR control. Nonlinear control are also concerned. In this case, hierarchical sliding mode control is examined due to its successful operation on under-actuated SIMO system.

Then, from a similar form with IP, acrobot is concerned. Thence, based on acrobot structure, mathematical dynamic equations of a kind of two-legged robot with elastic legs are generated and analized. This robot can be considerred to be closed to athlete robot. Due to the complexity of complete mathematical dynamic equation, an approximated equivalent model of robot is presented. Under this equivalent model, LQR and hierarchical sliding mode control are examined sucessfully on simulation, only. Robot can stand on one leg. By the uncertainty of equivalent model, hierarchical sliding mode control is proven to be more efficient in this case. Beside robot with elastic legs, mathematical model of elastic inverted pendulum are presented and analyzed. PD and hierarchical sliding mode controllers are applied for these robot. Genetic algorithm are used to find or optimize controllers in both simulation and experiment.

Also, real experimental platforms of elastic inverted pendulum and robot with elastic legs are presented and experimental results under linear feedback controllers are introduced. Then, conclusion which summerized the content of thesis, the direction in the future for athlete robot object and methods ends the thesis.

Contents

Chapter 1 : INVERSE PENDULUM – BASIC MODEL OF ROBOT SYSTEM

IP is a basic model for control theory. Its history was begin by construction of Robege (1960). Then, some representative researchers, such as, Schaefer and Cannon (1966), Furuta et al. (1991) developed basic theory for this model [1]. In this period, researches on pendulum mostly are mathematical problems and this model is not popular as a model for widely researching in control engineering. But, after years of survey on theory and mathematics on IP, Furuta invented Rotary IP – Furuta pendulum – and opened the ability of real experiment for this kind of model [2]. Since then, a lot of researches are developed based on this pioneer invention. Its simple mechanical structure – with only one motor and two simple sensors which in most cases are two encoders [3] – makes fabrication to be possible in usual laboratories, even in undeveloped countries. Moreover, nonlinear and under-actuated characteristics in mathematics makes it an ideal model for most control theory experiment. And very fast, following this achievement, big amount of algorithms were tested both in algorithm theory and experiment [4], [5].

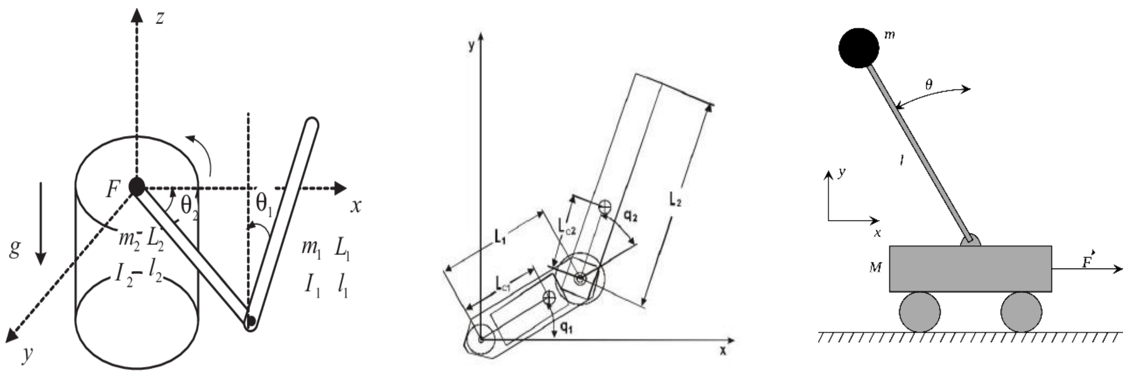


Fig 1.3 : Products stimulated by IP controlling

A lot of control algorithms are utilized to balance IP [4]. PID control [64], [65], has been proven to have good performances and control parameters are based on trial and error method [65] or searching algorithm, such as genetic algorithm [66] or LQR [36], [14], pole-placement control [67], [68]. The structure of these algorithms is simple and offers a lot of facilities for embedded systems. Fuzzy controller, which was presented by Zadeh in 1965 [69], represents also a good solution for developing new implementation techniques. Nonlinear control, especially SMC [70], introduces new robust algorithms that ensure a good stability of motion [71]. Hybrid controllers [18], [19], [59] have been presented to combine the advantages of intelligent systems with non linear algorithms.

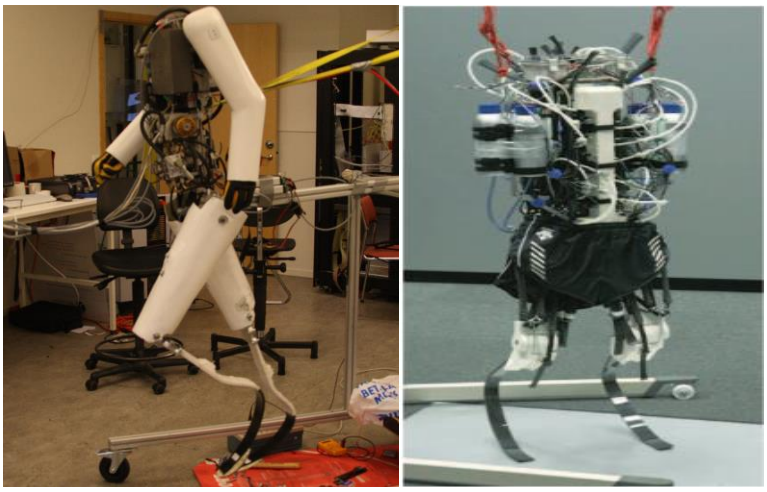


Figure 1.1: Dasher robot (left) and AR in Tokyo University (right)

Chapter 2: INVERSE PENDULUM-DYNAMICS

Beside the classical model-IP on cart, some other developed models are presented: more links are added to create double IP; changing in mechanical structure creates pendubot; replacing the position of actuator in pendubot creates acrobot. Dynamic equations are generated and they are the base for control algorithms in following sections. Under dynamic equations, a simple linear feedback controller is applied in some models before any other survey on other kinds of controllers. IP on cart (or Cart and Pole system) concludes of a cart, which moves in horizontal direction, and a pole, which rotates around an axis on cart.

a) Case 1: Distributed Mass Pendulum

We consider that the mass of pendulum is distributed along the length (Figure 2.1).

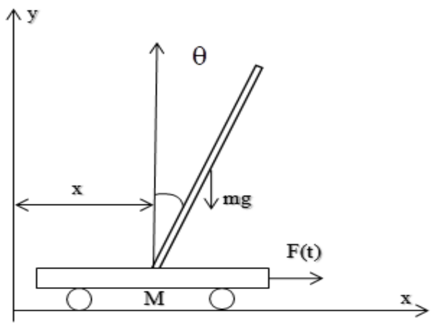


Figure 2.1: Cart and pole system with the pendulum as homogeneity

The dynamic model is inferred as

$$\ddot{x} = \frac{1}{\Gamma_1 + \Gamma_2 \sin^2\theta}\left[\Gamma_2 \sin\theta\left(L\dot{\theta}^2 - g\cos\theta\right) + F\right] \tag{2.1}$$

$$\ddot{\theta} = \frac{1}{L\left(\Gamma_1 + \Gamma_2 \sin^2\theta\right)}\left[-\Gamma_2 L\dot{\theta}^2 \sin\theta\cos\theta + \left(\Gamma_1 + \Gamma_2\right) g\sin\theta - F\cos\theta\right] \tag{2.2}$$

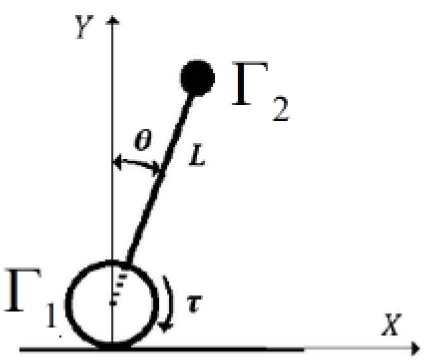


Figure 2.2: Balancing robot on wheel

For the balancing robot, equation of the system can be described as:

$$\ddot{x} = \frac{\Gamma_2 \sin\theta\left(L\dot{\theta}^2 - g\cos\theta\right) + \tau/r}{\Gamma_1 + \Gamma_2 \sin^2\theta} \tag{2.3}$$

$$\ddot{\theta} = \frac{-\Gamma_2 L\dot{\theta}^2 \sin\theta\cos\theta + \left(\Gamma_1 + \Gamma_2\right) g\sin\theta - \tau\cos\theta/r}{L\left(\Gamma_1 + \Gamma_2 \sin^2\theta\right)} \tag{2.4}$$

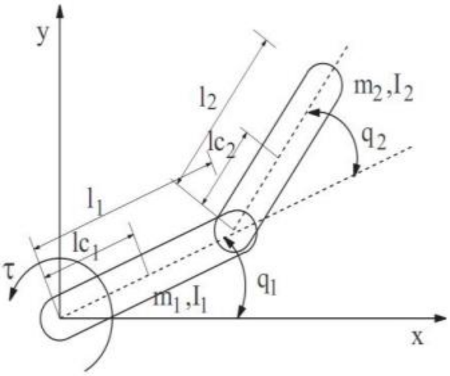


Figure 2.3: Mathematical structure of Pendubot

The dynamic equations of Pendubot are inferred as

$$\ddot{q}_1 = \frac{\begin{bmatrix} \beta_2\tau_1 + \beta_2\beta_3\left(x_2 + x_4\right)^2 \sin x_3 + \beta_3^2 x_2^2 \sin x_3 \cos x_3 + \\ -\beta_2\beta_4 g\cos x_1 + \beta_3\beta_5 g\cos x_3 \cos\left(x_1 + x_3\right) \end{bmatrix}}{\beta_1\beta_2 - \beta_3^2 \cos^2 x_3} \tag{2.5}$$

$$\ddot{q}_2 = \frac{\begin{bmatrix} \left(-\beta_2 - \beta_3\cos x_3\right)\tau_1 + \beta_4 g\left(\beta_2 + \beta_3\cos x_3\right)\cos x_1 + \\ -\beta_3\left(\beta_2 + \beta_3\cos x_3\right)\left(x_2 + x_4\right)^2 \sin x_3 + \\ -\beta_5 g\left(\beta_1 + \beta_3\cos x_3\right)\cos\left(x_1 + x_3\right) - \beta_3 x_2^2 \sin x_3\left(\beta_1 + \beta_3\cos x_3\right) \end{bmatrix}}{\beta_1\beta_2 - \beta_3^2 \cos^2 x_3} \tag{2.6}$$

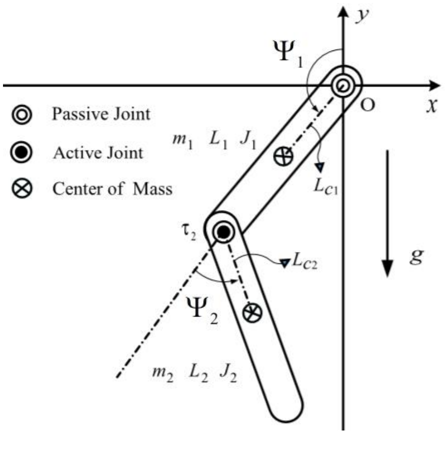


Figure 2.4: Model of acrobot

Considering that the friction is very small, the dynamic equations are

$$\frac{d}{dt}\left[\frac{\partial L(\Psi,\dot{\Psi})}{\partial \dot{\Psi}_i}\right]-\frac{\partial(\Psi,\dot{\Psi})}{\partial \Psi_i}=\tau_i,\left(i=1,2\right) \tag{2.7}$$

Because $\tau_1 = 0$ due to mechanical structure of acrobot, (2.7) becomes

$$M(\Psi_2)\ddot{\Psi}+C(\Psi,\dot{\Psi})\dot{\Psi}+G(\Psi)=\begin{bmatrix}0 & \tau_2\end{bmatrix}^T \tag{2.8}$$

where

$$C(\Psi,\dot{\Psi})=\begin{bmatrix}-\Phi_3\dot{\Psi}_2\sin\Psi_2 & -\Phi_3(\dot{\Psi}_1+\dot{\Psi}_2)\sin\Psi_2\\ \Phi_3\dot{\Psi}_1\sin\Psi_2 & 0\end{bmatrix};$$

$$G(\Psi)=\begin{bmatrix}G_1(\Psi)\\ G_2(\Psi)\end{bmatrix}=\begin{bmatrix}-\Phi_4\sin\Psi_1-\Phi_5\sin(\Psi_1+\Psi_2)\\ -\Phi_5\sin(\Psi_1+\Psi_2)\end{bmatrix}$$

Chapter 3: LYAPUNOV BASED ALGORITMS FOR INVERSE PENDULUM MODELS

3.1. Lyapunov method for Cart and Pole

Consider the dynamic model of the Cart and Pole system.

Theorem 3.1: For the system that describes this dynamic model, if the control law is

$$u = \frac{\sigma_1}{\varepsilon_1} x_1 + \frac{\sigma_2}{\varepsilon_2} x_2$$

where the coefficients $\sigma_1 > 0$, $\sigma_2 > 0$, α **,** β **,** γ satisfy the following conditions:

$$\sigma_1 > \varepsilon_{1\max} \quad (3.2)$$

$$\sigma_1 + \sigma_2 \delta > \alpha + \varepsilon_{1\max} \beta \quad (3.3)$$

$$\left(\varepsilon_{1\min} - \sigma_1\right)\delta + \frac{1}{4}\left(\sigma_1 + \sigma_2\delta - \alpha - \varepsilon_{1\max}\beta\right) < 0 \quad (3.4)$$

$$\delta - \sigma_1\beta + \varepsilon_2\beta + \varepsilon_2\beta\eta_1\eta_2 + \sigma_1 + \sigma_2\delta - \alpha - \varepsilon_{1\max}\beta < 0 \quad (3.5)$$

$$\alpha > \frac{\delta}{4} > 0 \quad (3.6)$$

$$\beta > 2\delta \quad (3.7)$$

The system is asymptotically stable.

3.2. Robust control

Consider the dynamic equations of IP model and the dynamic equations are presented in matrix form:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \varepsilon_1 & -\varepsilon_2 x_1 x_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -\varepsilon_3 \end{bmatrix} u \quad (3.8)$$

where the state constraints (sector-type) are defined as

$$-\eta_1 \le x_1 \le \eta_1; \quad (3.9)$$

$$-\eta_2 \le x_2 \le \eta_2$$

Theorem 3.2: Consider the IP model (3.8) and control law

$$u = -ky \quad (3.10)$$

where the range of variables is constrained by (3.9)

If there exists parameters γ , k , c_1 , c_2 , c_3 , c_4 , c_5 , c_6 that satisfy these conditions

$$0 < \gamma \le 4 \tag{3.11}$$

$$0 < k < \frac{1}{2\sqrt{\gamma}} \tag{3.12}$$

$$0 \le \gamma + 2\,\mathrm{Re}\left\{ \left(\frac{C}{2} \right)^T \left(j\omega I - A \right)^{-1} B \right\} \tag{3.13}$$

then, this model is asymptotically stabilized

3.3. Fuzzy-Lyapunov based Algorithm for IP models

Consider a nonlinear system of IP model described by

$$\dot{x} = \Delta f\left(x\right) + f\left(x\right) + \left(b + \Delta b\right)u\,,\ x\left(0\right) = x_0 \tag{3.14}$$

where: $\Delta f\left(x\right)$ and Δb represent the uncertainty of $f\left(x\right)$ and b , respectively

Fuzzy model can be described by r fuzzy rules. The i[th] rule is

If z_1 is F_{i1} and z_2 is F_{i2} and … and z_p is F_{ip} then

$$\dot{x} = \left(B^i + \Delta B^i\right)u + \left(A^i + \Delta A^i\right)x \tag{3.15}$$

$$F_{ij}\left(x_i\right) = \begin{cases} 1 - \dfrac{\left|x_i - j_i\tilde{\Delta}\right|}{\tilde{\Delta}} & \left|x_i - j_i\tilde{\Delta}\right| < \tilde{\Delta} \\ 0 & elsewhere \end{cases} \tag{3.16}$$

Theorem 3.3: Consider the control law is PD form with k is feedback matrix. If following conditions are verified:

a) $k_{\min} \le k \le k_{\max}$

b) $\mathrm{Re}\left\{ c^T \left(j\omega I - H \right)^{-1} \hat{b} \right\} + \left(k_{\max}^{-1} - \varepsilon^{-1}\beta \right) \ge 0$

where $H = \left(A^1 + \nu I - k_{\min} M \right)$ is Hurwitz and $\hat{b} = b^1 - d / k$

c) The pair $\left(H, \hat{b} \right)$ is controllable

Then, this model is asymptotically stabilized.

Chapter 4: FUZZY CONTROL FOR INVERSE PENDULUM MODELS

4.1. Lyapunov Method based Fuzzy Controller.

The knowledge of experts and the GA method do not guarantee the mathematical stabili system under fuzzy controller. Thence, Lyapunov criterion can be used to designed a f controller. We consider the IP model, Lyapunov function is selected as:

$$V=\frac{1}{2}\left(\alpha x_1^2+\beta x_2^2+2\delta x_1 x_2\right)\geq\frac{1}{2}\left[\left(\alpha-\frac{\delta}{2}\right)x_1^2+\left(\beta-2\delta\right)x_2^2\right] \qquad (4.1)$$

The derivative with respect time is

$$\dot{V}=\chi-\varepsilon_3\vartheta u \qquad (4.2)$$

where $\chi=5\varepsilon_1 x_1 x_2+2x_2^2-5\varepsilon_2 x_1 x_2^3-2\varepsilon_2 x_1^2 x_2^2+2x_1 x_2$; $\vartheta=2x_1+5x_2$

By using Lyapunov method, the stability of motion is obtained if the function (4.2) is negative definite. The new fuzzy controller has to implement these conditions.

Table 1: Selection condition of control signal to satisfy Lyapunov criterion

Condition of variables			Condition of control signal to keep system stable
$\vartheta>0$	$x_1x_2>0$	$\chi\geq 0$	$u\geq\chi/\left(\varepsilon_{3\min}\vartheta\right)$
		$\chi<0$	$u\geq\chi/\left(\varepsilon_{3\max}\vartheta\right)$
	$x_1x_2<0$	$\chi\geq 0$	$u\geq\chi/\left(\varepsilon_{3\min}\vartheta\right)$
		$\chi<0$	$u\geq\chi/\left(\varepsilon_{3\max}\vartheta\right)$
$\vartheta<0$	$x_1x_2>0$	$\chi\geq 0$	$u\leq\chi/\left(\varepsilon_{3\min}\vartheta\right)$
		$\chi<0$	$u\leq\chi/\left(\varepsilon_{3\max}\vartheta\right)$
	$x_1x_2<0$	$\chi\geq 0$	$u\leq\chi/\left(\varepsilon_{3\min}\vartheta\right)$
		$\chi<0$	$u\leq\chi/\left(\varepsilon_{3\max}\vartheta\right)$

Memberships of variables x_1 and x_2 are shown in Figure 4.1 and Figure 4.2. From column 1, 2 of Figure 4.3 and Table 1, the range of controller is shown in the column 3 of Table 1. Then, appropriate memberships for output are selected in Figure 4.3.

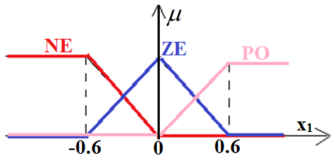


Figure 4.1: Memberships of x_1

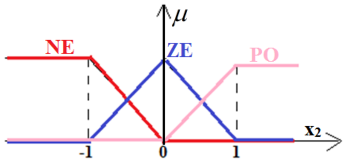


Figure 4.2: Memberships of x_2

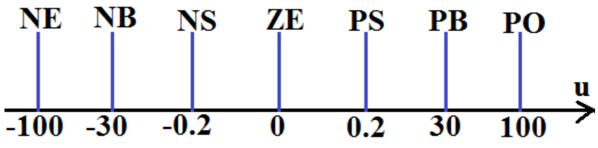


Figure 4.3: Memberships of output

4.2. Hybrid Controller.

Sliding Mode Control represents a very good technique for controlling the nonlinear systems by fuzzy techniques. Also, this method can be developed as a hierarchical structure for cascade connections of the IP models [54]-[58].

Assume that a dynamic equations of a Single Input Multiple Output (SIMO) system are

$$\ddot{\alpha}_i = A_i(\alpha_i) + B_i(\alpha_i)u \qquad (4.3)$$

where α_i, α_{di} : state variables, reference signal of each variable; u : control input signal

Denote: $e_i = \alpha_i - \alpha_{di}$ (4.4)

as the error between state variable and reference signal

From (4.3), (4.4) the equivalent equations of system will be

$$\ddot{e}_i = f_i + g_i u \qquad (4.5)$$

A controller can be designed for system (4.5) to stabilize variables $e_i \xrightarrow{t\to\infty} 0$ or $\alpha_i \xrightarrow{t\to\infty} \alpha_{id}$.

In Figure 4.4, a structure of hierarchcal sliding surfaces is presented.

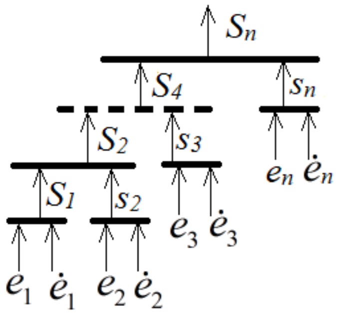


Figure 4.4: Hierarchical sliding surfaces structure for system

Sliding surfaces are denote as

$$s_k = c_k e_k + \dot{e}_k \ (k \le n) \qquad (4.6)$$

$$S_k = a_{k-1}S_{k-1} + s_k \ \left(k \le n\right) \tag{4.7}$$

where $a_{i-1} = const$; $a_0 = S_0 = 0$.

$$S_k = \sum_{r=1}^{k}\left(\prod_{j=r}^{k} a_j\right) s_r \ \left(k \le n\right) \tag{4.8}$$

From (4.8), it yields

$$\dot{S}_k = \sum_{r=1}^{k}\left(\prod_{j=r}^{k} a_j\right) \dot{s}_r \ \left(k \le n\right) \tag{4.9}$$

The k^{th} layer SMC law is defined as

$$u_k = u_{k-1} + u_{eqk} + u_{swk} \ \left(k \le n\right) \tag{4.10}$$

u_{swk} , u_{eqk} is defiend as switching and equivalent control law for k^{th} layer.

The final control signal is infered

$$u_n = \frac{\left[\sum_{r=1}^{n}\left(\prod_{j=r}^{n} a_j\right) b_r u_{eqr} - \eta_n \operatorname{sgn} S_n - \xi_n S_n\right]}{\sum_{r=1}^{n}\left(\prod_{j=r}^{n} a_j\right) b_r} \tag{4.11}$$

<u>Theorem 4.1</u> For these dynamic equations, the sliding surfaces and control law specified in the previous part, the surface S_k is asymptotically stable.

Chapter 5: INVERSE PENDULUM MODELS WITH ELASTIC COMPONENTS

5.1. Elastic Inverted pendulum

In the previous sections, The IP models [105], [106], are based on the assumption that the pendulum bar is rigid. In all these cases, the model dynamics are defined by lumped parameter systems. In real appications , the mechanical architecture of the IP model contains flexible bars (Elastic IP model-E-IP model) that impose a new mathematical treatement, in which the bar dynamics are described by Partial Differential Equaions (PDE).

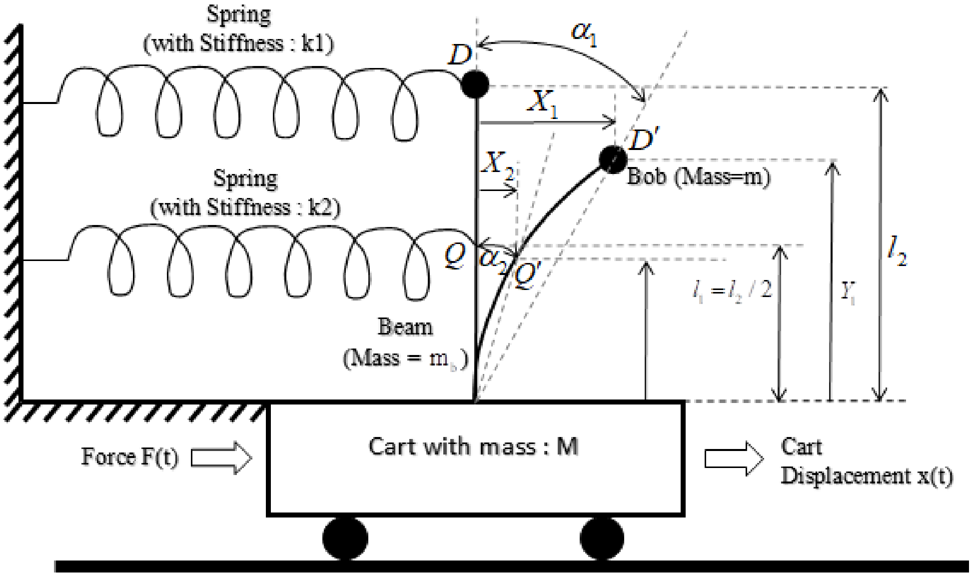


Figure 5.1: E-IP with tip mass is fixed on cart

Illustrative example of E-IP models are shown in Figure 5.1, Figure 5.2. In literature, few researchers investigate the control problem of these models [73]-[75] but they do not use a rigorous mathematical suport for the controller design. Also, the performances achieved by proposed algorithms do not prove the quality of controllers.

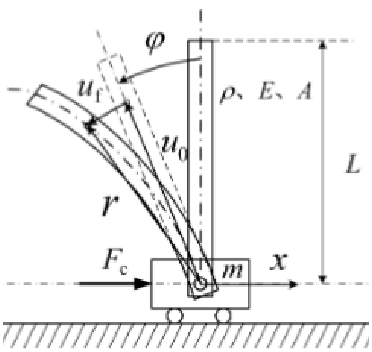


Figure 5.2: E-IP un-fixed on Cart

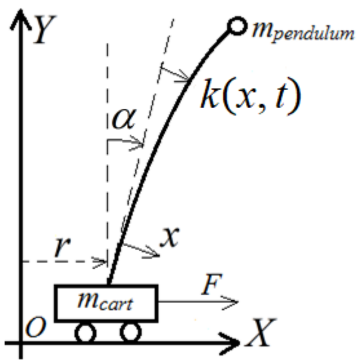


Figure 5.3: E-IP on Cart

According the Hamilton's principle

$$\int_{t_1}^{t_2} \left(\delta T - \delta V + \delta W_{nc} \right) dt = 0$$

where δT, δV, δW_{nc} represent the variational components of the kinetic, potential and non-conservative work.

The dynamic model will be

$$-\left(m_{cart} + \rho l + m_{pendulum}\right)\ddot{r} - \left(m_{pendulum} l + \rho \frac{l^2}{2}\right)\ddot{\alpha}\cos\alpha +$$

$$+m_{pendulum}\begin{bmatrix} \ddot{\alpha} \times k\left(l,t\right)\sin\alpha - \dot{k}\left(l,t\right) \times \cos\alpha + \\ +2\dot{\alpha} \times \dot{k}\left(l,t\right)\sin\alpha + \dot{\alpha}^2 \times k\left(l,t\right) \times \cos\alpha \end{bmatrix} +$$

$$+\left(\rho\frac{l^2}{2} + m_{pendulum} l\right)\dot{\alpha}^2 \sin\alpha + \rho\int_0^l \begin{pmatrix} \ddot{\alpha} k \times \sin\alpha - \ddot{k} \times \cos\alpha + \\ +2\dot{\alpha}\dot{k} \times \sin\alpha + \dot{\alpha}^2 k \times \cos\alpha \end{pmatrix} dx + F = 0$$

$$-\left(J + m_{pendulum} l^2 + \rho\frac{l^3}{3}\right)\ddot{\alpha} - \left(m_{pendulum} l + \rho\frac{l^2}{2}\right)\ddot{r} \times \cos\alpha +$$

$$+m_{pendulum}\begin{bmatrix} \ddot{r} k\left(l,t\right) \times \sin\alpha - \ddot{\alpha} k^2 \times \left(l,t\right) - l\ddot{k}\left(l,t\right) + \\ -2\dot{\alpha} \times k\left(l,t\right) \times \dot{k}\left(l,t\right) + gk\left(l,t\right) \times \cos\alpha \end{bmatrix} +$$

$$+\rho\int_0^l \left(\ddot{r} k \times \sin\alpha - \ddot{\alpha} k^2 - \ddot{k} x - 2\dot{\alpha} k \dot{k} + gk \times \cos\alpha\right) dx +$$

$$+\left(m_{pendulum} g l + \rho \mathrm{g} \frac{l^2}{2}\right)\sin\alpha = 0$$

$$m_{pendulum}\left[k\left(l,t\right) \times \dot{\alpha}^2 - \ddot{k}\left(l,t\right) - l\ddot{\alpha} - \ddot{r} \times \cos\alpha + g\sin\alpha\right] + EI \times k'''\left(l,t\right) = 0$$

$$\rho\left(k\dot{\alpha}^2 - \ddot{k} - \ddot{\alpha} x - \ddot{r} \times \cos\alpha + g \times \sin\alpha\right) - EI \times k'''' = 0$$

$$k'''\left(0,t\right) = k''\left(0,t\right) = k''\left(l,t\right) = 0$$

Define $\Psi_i\left(t\right)$, $X_i\left(x\right)$ as function of time of i^{th} mode shape and function of mode shape of point x and $k\left(x,t\right)$ can be assumed to be $k\left(x,t\right) = \sum_{i=1}^{n} \Psi_i\left(t\right) X_i\left(x\right)$ [76]. We take into account only the first mode-shape . The dynamic equations of system are:

$$
-\left(m_{cart}+\rho l+m_{pendulum}\right)\ddot{r}-\left(m_{pendulum}l\rho\frac{l^2}{2}\right)\ddot{\alpha}\cos\alpha+m_{pendulum}\begin{bmatrix}X(l)\Psi\ddot{\alpha}\sin\alpha+\\-X(l)\dot{\Psi}\cos\alpha+\\+2X(l)\dot{\Psi}\dot{\alpha}\sin\alpha+\\+X(l)\Psi\dot{\alpha}^2\cos\alpha\end{bmatrix}+
$$

(5.6)

$$
+\left(\rho\frac{l^2}{2}+m_{pendulum}l\right)\dot{\alpha}^2\sin\alpha+\rho\xi_1\Psi\ddot{\alpha}\sin\alpha-\rho\xi_1\ddot{\Psi}\cos\alpha+2\rho\xi_1\dot{\Psi}\dot{\alpha}\sin\alpha+
$$

$$
+\rho\xi_1\Psi\dot{\alpha}^2\cos\alpha+F=0
$$

7)

$$
-\left(J+m_{pendulum}l^2+\rho\frac{l^3}{3}\right)\ddot{\alpha}-\left(m_{pendulum}l+\rho\frac{l^2}{2}\right)\ddot{r}\cos\alpha+\rho g\xi_1\cos\alpha\Psi+
$$

$$
+\left(m_{pendulum}gl+\rho g\frac{l^2}{2}\right)\sin\alpha+m_{pendulum}\begin{bmatrix}X(l)\Psi\ddot{r}\sin\alpha-X^2(l)\Psi^2\ddot{\alpha}+\\-X(l)\ddot{\Psi}l-2X^2(l)\Psi\dot{\Psi}\dot{\alpha}+\\+X(l)\Psi g\cos\alpha\end{bmatrix}+
$$

$$
+\rho\xi_1\ddot{r}\Psi\sin\alpha-\rho\xi_2\Psi^2\ddot{\alpha}-\rho\xi_3\ddot{\Psi}-2\rho\xi_2\Psi\dot{\Psi}\dot{\alpha}=0
$$

$$
m_{pendulum}\left[X(l)\Psi\dot{\alpha}^2-X(l)\ddot{\Psi}-l\ddot{\alpha}-\ddot{r}\cos\alpha+g\sin\alpha\right]+\xi_4\Psi=0
$$

8)

5.2. Elastic C-shaped Leg Models.

C-haped legs represent a special architecture of compliant elastic legs have been introduced to make the motion of two-legged robot more flexible

Figure 5.4: Curved beam

Shear:	$F_r = F\cos\theta$	(5.9)
Axial:	$F_\theta = F\sin\theta$	(5.10)
Bending moment:	$M = FR\sin\theta$	(5.11)

Strain energy due to bending moment M is

$$
U_1=\int\frac{M^2}{2AeE}d\theta \qquad (5.12)
$$

where e is eccentricity which is calculated as $e = R - r_n$. If assuming that $R/h > 10$, it yields

$$U_1 = \int \frac{M^2 R}{2EI} d\theta \qquad (5.13)$$

Strain energy due to axial force F_θ is

$$U_2 = \int \frac{F_\theta^2 R}{2AE} d\theta \qquad (5.14)$$

Strain energy due to moment which is created by axial force F_θ is

$$U_3 = -\int \frac{MF_\theta}{AE} d\theta \qquad (5.15)$$

The sign “-” in (5.15) is caused by the opposite direction of deflection to force F

$$U_4 = C\int \frac{F_r^2 R}{2AG} d\theta \qquad (5.16)$$

The Hook’s law for linear spring is

$$F = k\delta \qquad (5.17)$$

where: F is the force that applies on spring through the length of spring; k is the constant of the spring; δ is the deflection of the spring.

When consider C-shaped leg, the parameter k is not the constant when regarding this kind of leg as a linear spring. The value of k is different in each situation of leg when touching the ground.

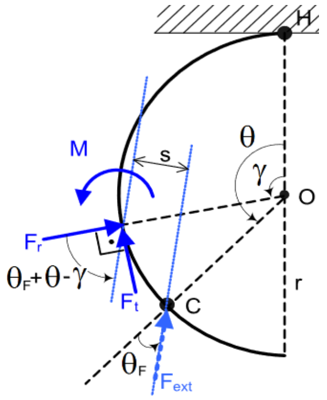


Figure 5.5: Cross section of C-shaped leg

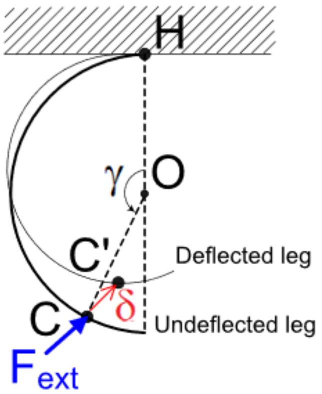


Figure 5.6: Effect of external force to C-shaped leg

5.3. C-shaped Leg Robot Control by Lyapunov Methods.

Considering that two legs of robot have the same behavior, motion of robot with elastic legs is devided into two phases: stance and flight phase. In stance phase, legs touch the ground in all period. Otherwise, legs are off ground in all period of flight phase. A PD controller which is designed based on Lyapunov stability’s theorem is surveyed.

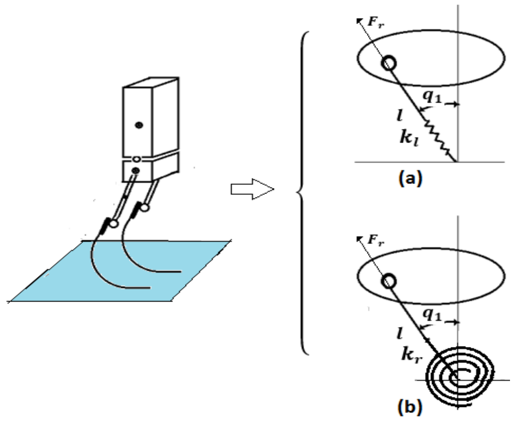


Figure 5.7: Equivalent IP model of robot with compliant legs, where:
a/ linear spring/b)rotational spring

Rotational deflection of elastic leg is

$$\delta_r \approx \frac{\partial U}{\partial M} \qquad (5.18)$$

It yields

$$k_l \approx \frac{M}{\delta_l} = \frac{4EI}{R^2\left\{\pi + \frac{1}{2}\left[\sin(2\varphi) + \sin(2[\pi - \varphi])\right]\right\}}$$

Considering the elastic leg is hard and variation of shape in linear spring is small, by using Lagrange method, equations of stance phase in Figure 5.7b are obtained as

$$\left(M^* l^2 + I^*\right)\ddot{q}_1 = M^* gl \sin q_1 - k_r(\varphi) q_1 + \tau_1^* + h\left(\tau_2, \tau_3, q_2, q_3\right) \qquad (5.19)$$

A PD linear feedback controller is suggested to be used in this case

$$\tau = -\mu_1 q_1 - \mu_2 \dot{q}_1 \qquad (5.20)$$

Theorem 5.1: If system (5.19) is controlled by (5.20)
where the control parameters satisfy the conditions

$$\sqrt{\frac{k_r}{\mathbb{N}}} > \alpha > 0\,,\ \eta > 0 \qquad (5.21)$$

$$\mu_1 > 0\,;\ \mu_2 > 0 \qquad (5.22)$$

$$\begin{bmatrix} \mu_2 - \alpha\mathbb{N} - \eta & \frac{1}{2}\left(\mu_2 + \alpha\mu_2 - mgl\right) \\ \frac{1}{2}\left(\mu_1 + \alpha\mu_2 - mgl\right) & \alpha\left(k_{r\max} + \mu_1 - mgl - \eta\right) \end{bmatrix} > 0 \qquad (5.23)$$

where: $\mathbb{N} = M^* l^2 + I^*$

then, this system is stable

Chapter 6: JUMPING MOTION CONTROL ALGORITHMS

A multi-body robot system in Figure 6.1 was concerned to survey the jumping behaviour. There are two legs to determine the motion. Each leg concludes of two components:

- the lower part (foot) with a hybrid pneumatic/electro-hydraulic actuator and ER-fluid damper.
- The upper leg with a conventional electric drive.

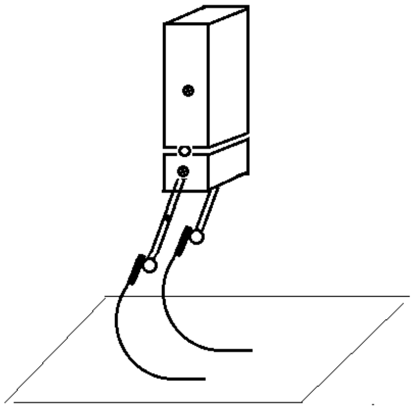


Figure 6.1: Model structure of jumping robot

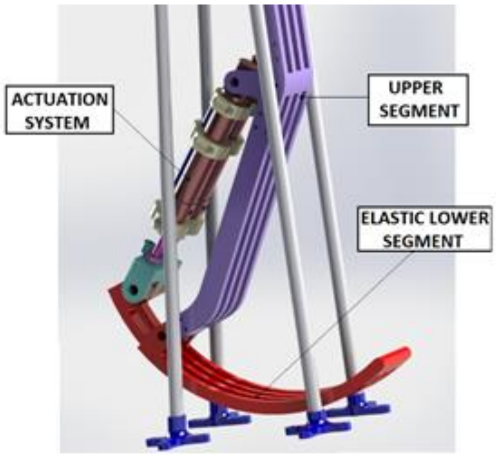


Figure 6.2: Platform of jumping robot

In order to simplify the technological problem, we considering that in jumping motion, two legs have the same posture. The mathematical model is not used and the structure of model in this section is described in Figure 6.2.
Similarly to walking model, jumping concludes two phases but these phases are defined diferrently: stance and flight phase. In stance phase, one foot touches the ground. And, in flight phase, both legs are off the ground. The boundary of these two phases are defined as two motions conditions: touch-down and take-off. These motions create a sequence when robot hits the ground (landing impact sequence) and when robot takes off the ground. This cycle is repeated periodically by robot (Figure 6.3, Figure 6.4). The feet is assumed not to slip beyond surface of the ground and always stay on contact with the ground when touching the ground.

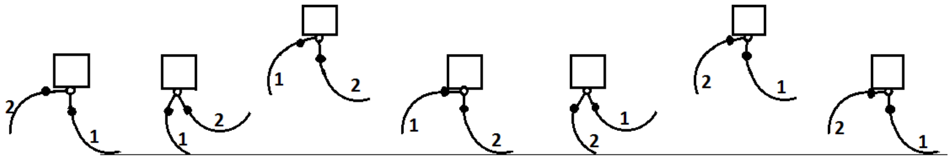


Figure 6.3: Cycle of motion

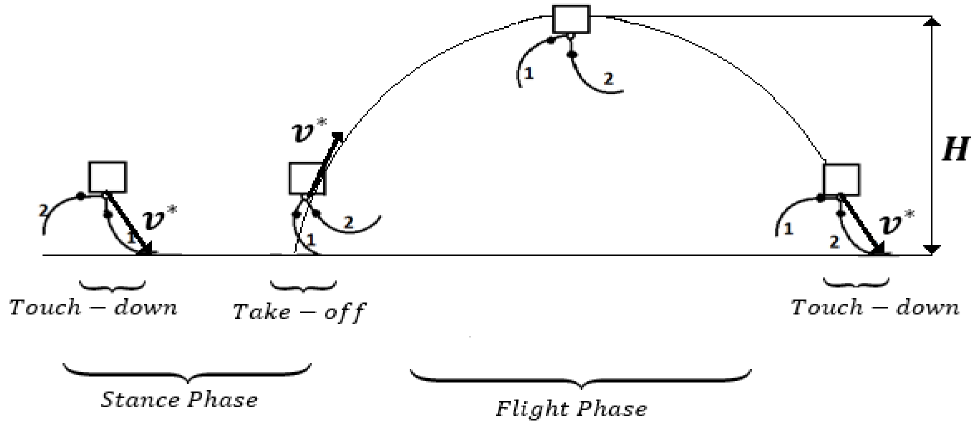


Figure 6.4: Trajectory of jumping motion

6.1. Stance Phase Model

This phase is determiner by contact between the ground and the leg in Figure 6.5

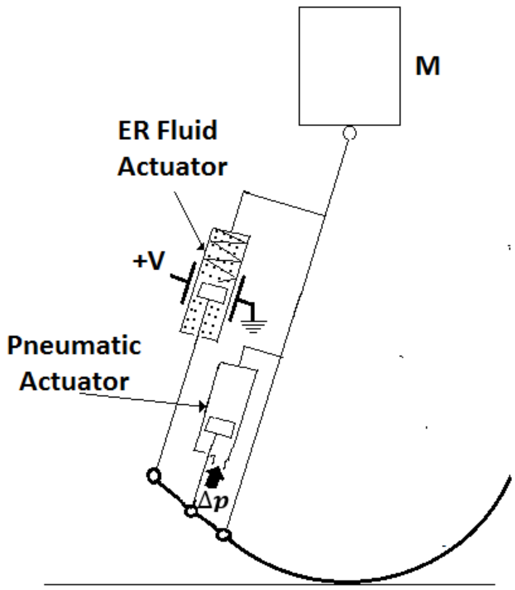


Figure 6.5: mechanical structure of leg for jumping robot

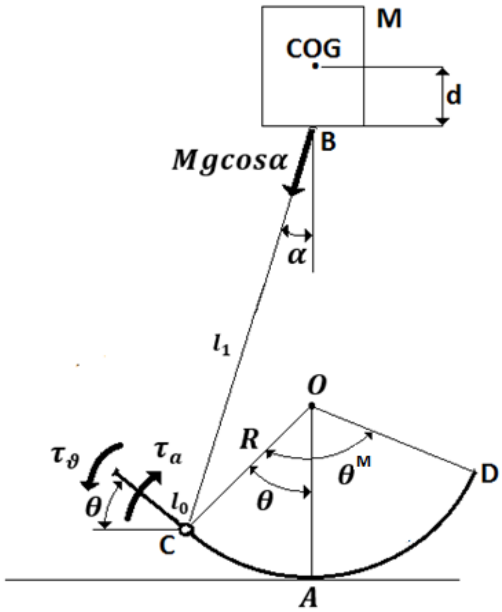


Figure 6.6: mathematical structu for jumping robot

The dynamic model

$$M\left(d+l_1\right)^2\ddot{\theta}+MgR\sin\theta+2EI\theta+\tau_{\vartheta}=\tau_a-\vartheta_0\dot{\theta} \qquad (6.1)$$

The initial condition of (6.1) is

$$\theta(0)=\theta_0 \qquad (6.2)$$

Or

$$M\left(d+l_1\right)^2\ddot{\theta}+J\ddot{\theta}+\vartheta_0\dot{\theta}+K_e\theta=\tau_a-\tau_{\vartheta} \qquad (6.3)$$

where the equivalent elastic coefficient of the foot is defined as (when regarding

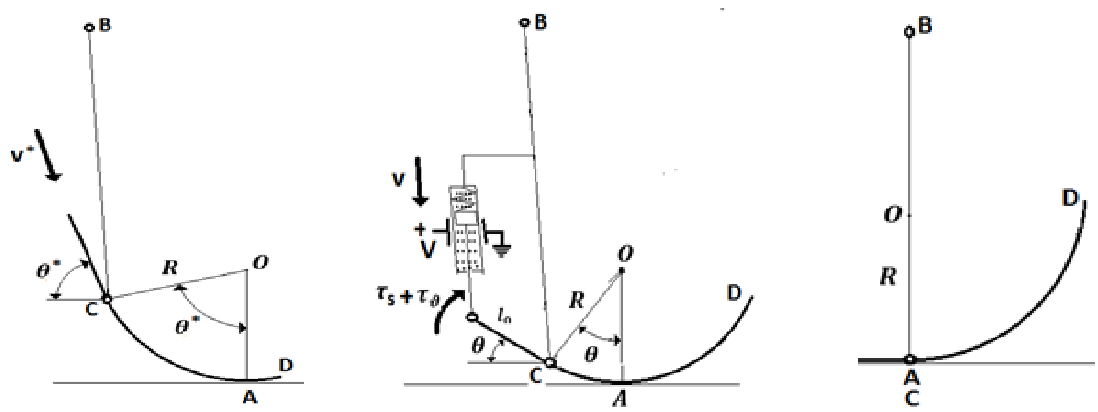
$\sin\theta \approx \theta$)

$$K_e = MgR + 2EI \tag{6.4}$$

and τ_g denotes the equivalent torque of the damper (the effect of the ER fluid and local.

6.2. *Stance Phase: Touch-Down Sequence*

Quality of motion in jumping period is important. The conventional feet discussed in [93] are based by passive dampers which consist of springs and mechanical elastic components. When the leg hits the ground, the damping force increases determining vibrations in mechanical structure that can disturb the evolution of the robot. It is necessary to select appropriate equivalent stiffness and damping coefficients to achieve the desired performances. For this reason, an active damper with ER fluids actuator and a skyhook viscocity controller is proposed (in Figure 6.5). The actuator consists of a cyclinder with piston, a spring and an ER fluid. The touch-down sequence starts at the instant when the elastic foot hits the ground. The main instant sequence is presented in Figure 6.7.



Touch-Down Sequence Initial State   Touch-Down Sequence Intermediate State   Touch-Down Sequ State

Figure 6.7: Touch-Down Sequence

<u>Case 1:</u> Actuator as passive damper system

The Touch-Down model is illustrated in Figure 6.8 where the spring K_f, K_s denotes te equivalent sprinf foefficient of elastic foot and elastic parameters, respectively, of the actuator that operates as a semi-active damper system. In this case, we assume that the active torque which is developed by actuator is zero ($\tau_a = 0$), and the actuator operates as a damper, only. This system varies the damping forces using a feedback determined by the dynamics of masses.

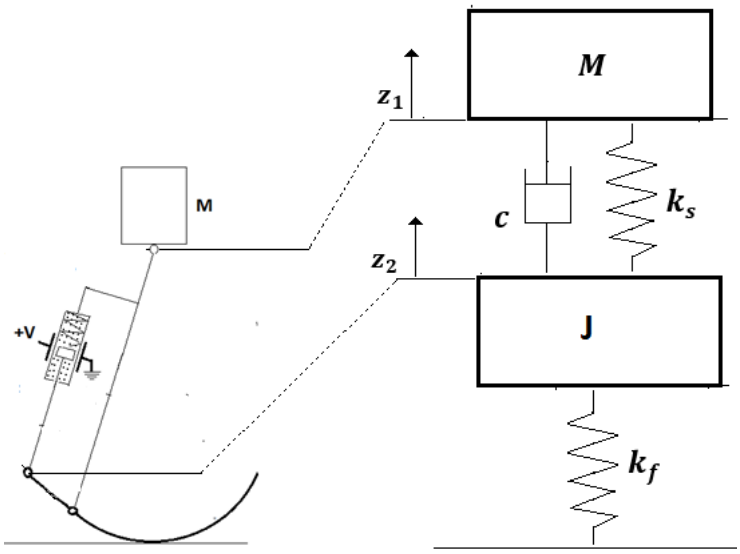


Figure 6.8: Touch-Down passive damper model

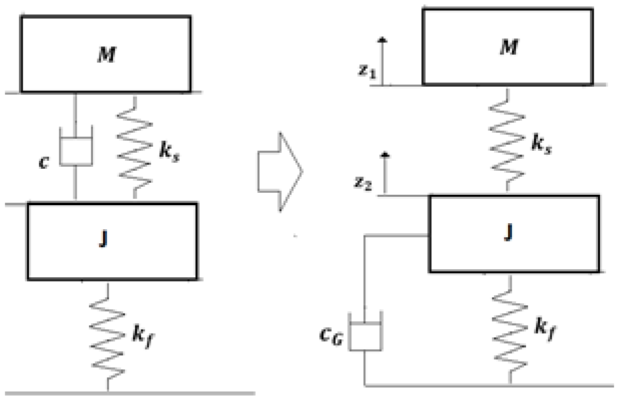


Figure 6.9: Ground-hook damper model

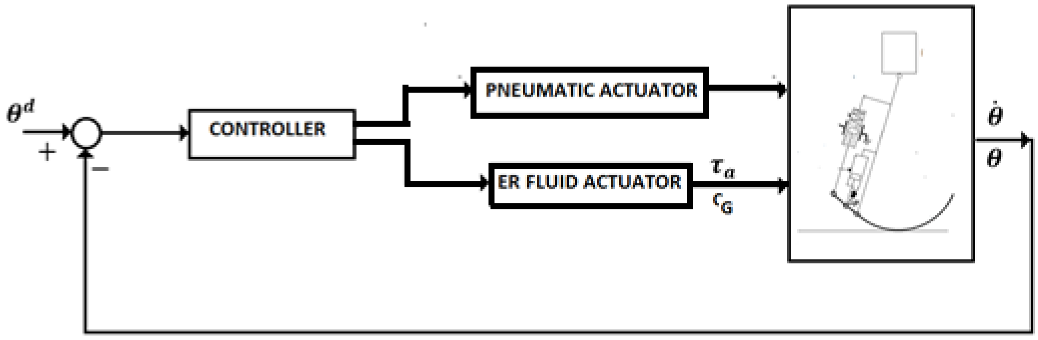


Figure 6.10: Touch-Down sequence control system

The dynamic behaviour of the passive model (in Figure 6.8) is described by using the same procedure as which was discussed in previous section.

$$\ddot{\theta}J = -\vartheta_0\dot{\theta} - MgR\sin\theta - 2EI\theta + K_S\left(z_1 - z_2\right)R^* + c\left(\dot{z}_1 - \dot{z}_2\right) \qquad (6.5)$$

where z_1, z_2 represent the vertical positions of the two links of leg (B, C); K_S and

R^* are the elastic coefficient of damper spring and equivalent radius of the damper motion.

$$R^* = l_0 \cos\theta + R\sin\theta \quad (6.6)$$

where c is the passive damping coefficient.

The quality of the system can be evaluated by the analysis of the transmissibility that is defined as in [96].

$$T(\omega) = z_2(\omega)/z_1(\omega) \quad (6.7)$$

Where

$$z_1 = l_0 \sin\theta + R(1-\cos\theta) + l_1 \cos\alpha \quad (6.8)$$

$$z_2 = l_0 \sin\theta + R(1-\cos\theta) \quad (6.9)$$

The analyse of the transmissibility of the model which is described in (6.5) is complex due to nonlinear structure. Assuming that oscillations around equilibrium point A is small and the following constraint is verified

$$\left| R\theta / l_0 \right| < 1 \quad (6.10)$$

Then

$$z_2 \approx l_0\theta \quad (6.11)$$

$$R^* \approx l_0 \quad (6.12)$$

Substituting (6.11) and (6.12) into (6.5), we obtain

$$\ddot{z}_2 = -\frac{\vartheta_0 + c_G}{J}\dot{z}_2 - \frac{MgR + 2EI + K_S l_0^2}{J} z_2 + \frac{K_S l_0^2}{J} z_1 + \frac{c l_0^2}{J}\dot{z}_1 \quad (6.13)$$

Applying the Laplace transform, it yields

$$T(s) = \frac{z_2(s)}{z_1(s)} = \frac{K_S l_0^2 + \frac{c l_0^2}{J} s}{s^2 + \frac{\vartheta_0 + c_G}{J} s + \frac{MgR + 2EI + K_S l_0^2}{J}} \quad (6.14)$$

Substitute $s = j\omega$ into (6.14), we obtain

$$T(j\omega) = \frac{z_2(j\omega)}{z_1(j\omega)} = \frac{1 + 2\zeta(j\omega/\omega_n)}{-1 + (\omega/\omega_n)^2 + 2\zeta(\omega/\omega_n) j} \quad (6.15)$$

where ω_n is natural frequency of the system which is calculated as below

$$\omega_n = \sqrt{\frac{MgR + 2EI + K_S l_0^2}{J}} \quad (6.16)$$

and ζ is the equivalent passive damping factor ratios which is calculated as below

$$\zeta_p = \frac{\vartheta_0 + c}{2\sqrt{J\left(MgR + 2EI + K_S l_0^2\right)}} \qquad (6.17)$$

<u>Case 2:</u> Actuator as semiactive damper system (ground system)

A "Groundhook" strategy (in Figure 6.9) is proposed to facilitate the study of vibrations and to find control solutions to reduce vertical oscillatioins. A fictitous damper with equivalent viscosity coefficient c_G is considered between body and ground

$$c_G = \begin{cases} c_{\max}\dot{z}_2 & if \quad -\dot{z}_2\left(\dot{z}_1 - \dot{z}_2\right) > 0 \\ c_{\min}\dot{z}_2 & if \quad -\dot{z}_2\left(\dot{z}_1 - \dot{z}_2\right) < 0 \end{cases} \qquad (6.18)$$

A similar procedure results are shown in (6.19) below

$$\ddot{z}_2 = -\frac{\vartheta_0 + c_G}{J}\dot{z}_2 - \frac{MgR + 2EI + K_S l_0^2}{J} z_2 + \frac{K_S l_0^2}{J} z_1 \qquad (6.19)$$

which leads to

$$T(s) = \frac{z_2(s)}{z_1(s)} = \frac{K_S l_0^2}{s^2 + \frac{\vartheta_0 + c_G}{J}s + \frac{MgR + 2EI + K_S l_0^2}{J}} \qquad (6.20)$$

$$T(j\omega) = \frac{z_2(j\omega)}{z_1(j\omega)} = \frac{\eta}{-1 + \left(\frac{\omega}{\omega_n}\right)^2 + 2\zeta_G \frac{\omega}{\omega_n} j} \qquad (6.21)$$

where ω_n is natural frequency of system and shown in (6.16) and ζ_G is the equivalent damping factor ratios

$$\zeta_G = \frac{\vartheta_0 + c_G}{2\sqrt{J\left(MgR + 2EI + K_S l_0^2\right)}} \qquad (6.22)$$

$$\eta = \frac{K_S l_0^2}{MgR + 2EI + K_S l_0^2} \qquad (6.23)$$

<u>Case 3:</u> Actuator as ER Driver System

The actuator operates as ER driver system that develops an active torque τ_a

$$\ddot{\theta}J = -\vartheta_0\dot{\theta} - MgR\sin\theta - 2EI\theta + K_S\left(z_1 - z_2\right)R^* + c_\vartheta\left(\dot{z}_1 - \dot{z}_2\right) + \tau_a \qquad (6.24)$$

where c_ϑ is non-active value of the ER damping coefficient. Considering the constraint in (6.10), this model can be written as

$$\ddot{\theta} = -\frac{\vartheta_0 + c_\vartheta l_0^2}{J}\dot{\theta} - \frac{MgR + 2EI + K_S l_0^2}{J}\theta + \frac{K_S l_0}{J} z_1 + \frac{c_\vartheta l_0}{J}\dot{z}_1 + \frac{1}{J}\tau_a \qquad (6.25)$$

New state variables are defined as

$$\begin{cases} x = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T = \begin{bmatrix} \theta & \dot{\theta} \end{bmatrix}^T \\ \quad z = \begin{bmatrix} z_1 & z_2 \end{bmatrix}^T \end{cases} \qquad (6.26)$$

where z denotes the disturbance variable that modify the system behaviour.

The dynamic model becomes

$$\dot{x} = Ax + b\tau_a + Dz \qquad (6.27)$$

$$y = c^T x \qquad (6.28)$$

where

$$A = \begin{bmatrix} 0 & 1 \\ -\frac{MgR + 2EI + K_S l_0^2}{J} & -\frac{\vartheta_0 + c_\vartheta l_0^2}{J} \end{bmatrix};\ b = \begin{bmatrix} 0 \\ \frac{1}{J} \end{bmatrix};\ D = \begin{bmatrix} 0 & 0 \\ \frac{K_S l_0}{J} & \frac{c_\vartheta l_0}{J} \end{bmatrix}$$

The matrix A is stable but the stability, which describes system performance, is worser by the disturbance variable z. This disturbance can be evaluated in terms of state variables as

$$z_1 = \alpha\theta \ (\alpha < \alpha^*) \qquad (6.30)$$

$$z_2 = \beta\dot{\theta} \ (\beta < \beta^*) \qquad (6.31)$$

where α, β are positive constants. Therefore, the dynamic model in (6.27) becomes

$$\dot{x} = A^* x + b\tau_a \qquad (6.32)$$

Where

$$A^* = \begin{bmatrix} 0 & 1 \\ -\frac{MgR + 2EI + K_S l_0^2}{J} + \alpha & -\frac{\vartheta_0 + c_\vartheta l_0^2}{J} + \beta \end{bmatrix} \qquad (6.33)$$

Clearly, the disturbances z determine the instability of the system (A^* is an unstable matrix). The control law is proposed as

$$\tau_a = -ky \qquad (6.34)$$

Where $k = const > 0$ satisfies the sector condition below

$$k_{\min} \le k \le k_{\max} \qquad (6.35)$$

Theorem 6.1: The state vector $\begin{bmatrix} x_1 & x_2 \end{bmatrix}^T = \begin{bmatrix} \theta & \dot{\theta} \end{bmatrix}^T$ converges toward zero if the following conditions are satisfied

a) Matrix $H = A^* - E$ is Hurwitz, where $E = ec^T$ is a symmetrical matrix.

b) (H, b) is controllable and (H, c) is observable.

c) $\operatorname{Re}\left\{ \frac{c^T}{2} (sI - H)^{-1} \left(b - ek^{-1} \right) \right\} + k^{-1} \geq 0$

Proof:

Selecting Lyapunov function as

$$V = \frac{x^T P x}{2}$$

where P is a symmetrical positive definite matrix. Derivativing (6.37) by time and using (6.32), we obtain

$$\dot{V} = x^T \left[\left(A^* \right)^T + PA^* \right] x + 2x^T Pbu \qquad (6.38)$$

Or

$$\dot{V} = x^T \left\{ \left[\left(A^* \right)^T - E \right] P + P \left(A^* - E \right) \right\} x + 2x^T PEu + 2x^T Pbu \qquad (6.39)$$

Considering $E = wc^T$ and the control law in (6.34), the last two terms can be written as

$$2x^T PEx + 2x^T Pbu = 2x^T P (ex + bu) = 2x^T P \left(b - \frac{e}{k} \right) u \qquad (6.40)$$

From (6.35), after some calculations, it yields

$$\dot{V} \leq x^T \left\{ \left[\left(A^* \right)^T - E \right] P + P \left(A^* - E \right) \right\} x + 2x^T \left[P \left(b - \frac{e}{k} \right) - \frac{c^T}{2} \right] u - \frac{u^2}{k} \qquad (6.41)$$

By using the Yakubovich-Kalman-Popov Lemma [98] and conditions a, b, c of Theorem 6.1, it yields

$$\left[\left(A^* \right)^T - E \right] P + P \left(A^* - E \right) = -qq^T \qquad (6.42)$$

$$P \left(b - \frac{e}{k} \right) - \frac{c^T}{2} = q \sqrt{k^{-1}} \qquad (6.43)$$

Substituting (6.42), (6.43) into (6.41), we obtain

$$\dot{V} \le -\left(x^T q - u\sqrt{k^{-1}}\right)^2 < 0 \qquad (6.44)$$

Remark 6.1:

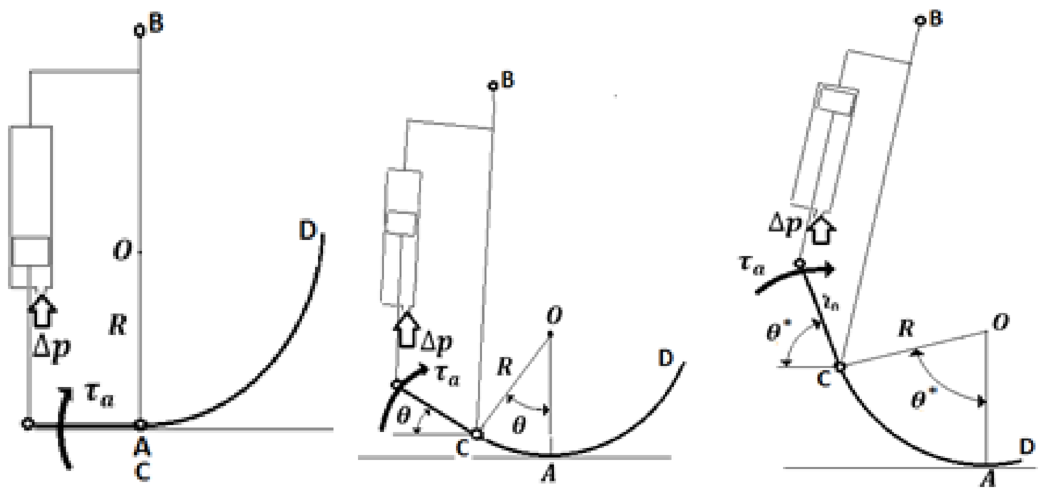
Define the transfer function $G(s)$ as follows

$$G(s) = \frac{c^T}{2}(sI - H)^{-1}\left(b - ek^{-1}\right) \qquad (6.45)$$

Considering the inequality (6.35) and condition c) of the Theorem 6.1 can be re-written as circle criterion [98]

$$\mathrm{Re}\left(\frac{k_{\max}^{-1} + G(j\omega)}{k_{\min}^{-1} + G(j\omega)}\right) > 0 \qquad (6.46)$$

6.3. Stance Phase: Take-off Sequence



Take-off Sequence Initial State

Take-off Sequence Intermediate State

Take-off Sequence Final State

Figure 6.11: Take-off Sequence

During this sequence, actuator system has to develop a sufficiently large energetic pulse to ensure a jumping motion on specified trajectory. This condition can be synthesized as

$$W(t) \ge W^* \qquad (6.47)$$

$$\frac{dW(t)}{dt} \ge \gamma > 0 \qquad (6.48)$$

where $W(0) = 0$ and W^* is critical energy that satisfies the trajectory parameters and $\gamma = const > 0$ determined by the take-off impulse.

Define υ^* the starting velocity on the flight trajectory for the position $\theta = \theta^*$ (in Figure 6.11c). The critical energy will be

$$W^* = \frac{1}{2} K_f \left(\theta^*\right)^2 + \frac{1}{2l_0^2} J \left(\dot{\theta}^*\right)^2 \quad (6.49)$$

Total active energy can be expressed as

$$W = w^T w = \frac{1}{2} K_f \theta^2 + \frac{1}{2} J \dot{\theta}^2 \quad (6.50)$$

where w is the energy component vector that is calculated as in (6.51) below and K_f is the equivalent elastic coefficient of the foot.

$$w = \begin{bmatrix} \dfrac{\theta}{\sqrt{\dfrac{2}{K_e}}} & \dfrac{\dot{\theta}}{\sqrt{\dfrac{2}{J}}} \end{bmatrix}^T$$

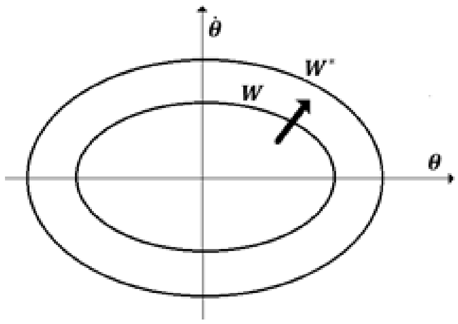


Figure 6.12: energy ellipsoid

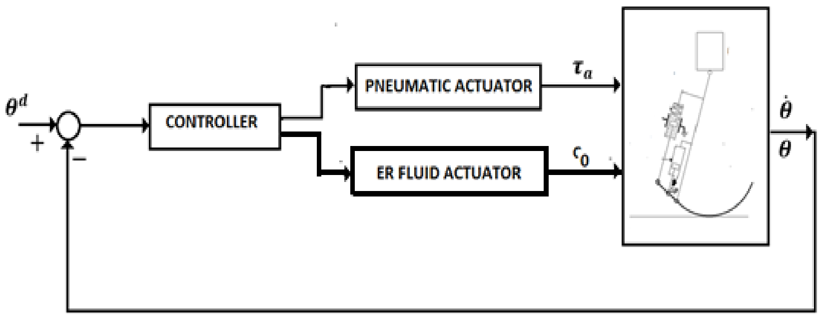


Figure 6.13: Take-off sequence control system

The constraint (6.47) is shown in the ellipsoid energy (in Figure 6.12) and the control system (in Figure 6.13) ensures the jumping conditions.

Theorem 6.2: The jumping conditions (6.47) and (6.48) are satisfied if the control law has the form below

$$\tau_a = -k_1^J \theta + k_2^J \dot{\theta} \quad (6.52)$$

where k_1^J, k_2^J are the controller gains, positive constants, that satisfy following conditions:

$$k_1^J > K_f - K_e \tag{6.53}$$

$$2k_2^J - k_1^J > 2\left(\vartheta_0 + c_0\right) - K_f + K_e \tag{6.54}$$

<u>Proof</u>

Dynamic model can be inferred from (6.1)-(6.3) where the damper is considered as a passive damper with the damping coefficient c_0 and the actuator operates as a pneumatic system that develops an active torque τ_a

$$\ddot{\theta}J = -\left(\vartheta_0 + c_0\right)\dot{\theta} - \left(MgR + 2EI\right)\theta + \tau_a \tag{6.55}$$

Where

$$\tau_a = \Delta pSl_0 \tag{6.56}$$

$\Delta p = p_f - p_0$ is the expression variation in the actuator and S is the area of piston surface.

The derivative of (6.49) will be

$$\dot{W} = K_f\theta\dot{\theta} + J\dot{\theta}\ddot{\theta} \tag{6.57}$$

Substituting the dynamic model in (6.53), it yields

$$\dot{W} = K_f\theta\dot{\theta} + \dot{\theta}\left[-\left(\vartheta_0 + c_0\right)\dot{\theta} - K_e\theta + \tau_a\right] \tag{6.58}$$

Substitute the control law in (6.52) into (6.58), we obtain

$$\dot{W} = \left(K_f - K_e - k_1^J\right)\theta\dot{\theta} + \left[k_2^J - \left(\vartheta_0 + c_0\right)\right]\dot{\theta}^2 \tag{6.59}$$

Then, by applying the inequality

$$\theta\dot{\theta} \geq -\frac{\theta^2}{2} - \frac{\dot{\theta}^2}{2} \tag{6.60}$$

(6.58) becomes

$$\dot{W} \geq \sigma_1\frac{\theta^2}{2} + \sigma_2\frac{\dot{\theta}^2}{2} \tag{6.61}$$

Where

$$\sigma_1 = k_1^J - K_f + K_e \tag{6.62}$$

$$\sigma_2 = 2k_2^J - k_1^J - 2\left(\vartheta_0 + c_0\right) + K_f - K_e \tag{6.63}$$

From (6.53), (6.54), it yield $\sigma_1 > 0$, $\sigma_2 > 0$. Combining with (6.61), we obtain

$$\dot{W} > \gamma > 0 \qquad (6.64)$$

Considering the following relations

$$\rho = 2\sigma_1 / K_f \; ; \; \sigma_2 = \rho \frac{J}{2} + \sigma_3 \qquad (6.65)$$

where $\sigma_3 = const > 0$, then, $\dot{W}$ can be written as

$$\dot{W} = \rho \frac{K_f}{2}\theta^2 + \left(\rho \frac{J}{2} + \sigma_3\right)\dot{\theta}^2 > \rho\left(\frac{1}{2}K_f\theta^2 + \frac{1}{2}J\dot{\theta}^2\right) = \rho W \qquad (6.66)$$

From (6.64) and (6.66), it can be concluded that W is an increasing positive definite function. For the final position of $\theta = \theta^*$, the limit value of $W = W^*$ is achieved.

Chapter 7: SIMULATION OF CONTROL ALGORITHMS

7.1. LQR Control Simulation of E-IP Model.

Consider the E-IP model (fig 5.3) and a LQR controller where the matrix R is assumed as identity matrix and the components of matrix Q are selected through GA. Simulating system under LQR controller in 10s with sample time as 10ms, there are 1001 samples of system response in a period of simulation time.

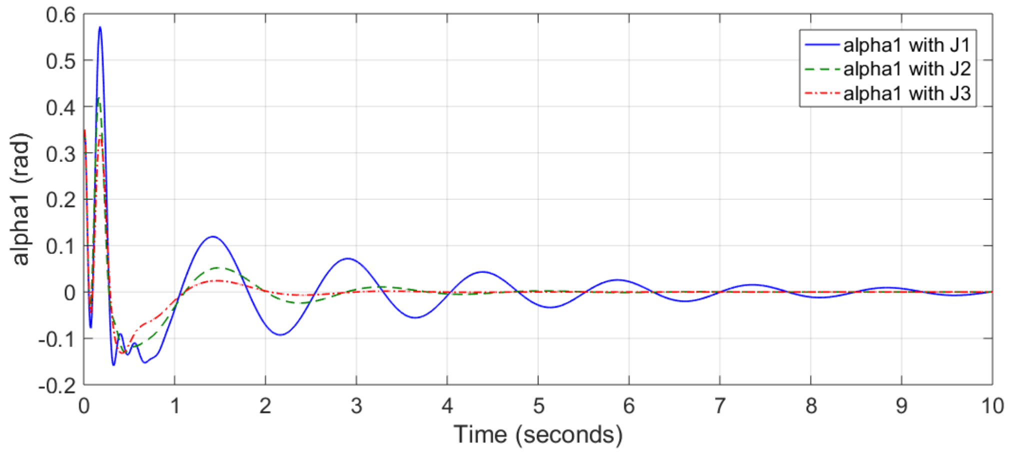


Figure 7.1: Comparison among responses of E-IP under LQR controllers through α_1 (rad)

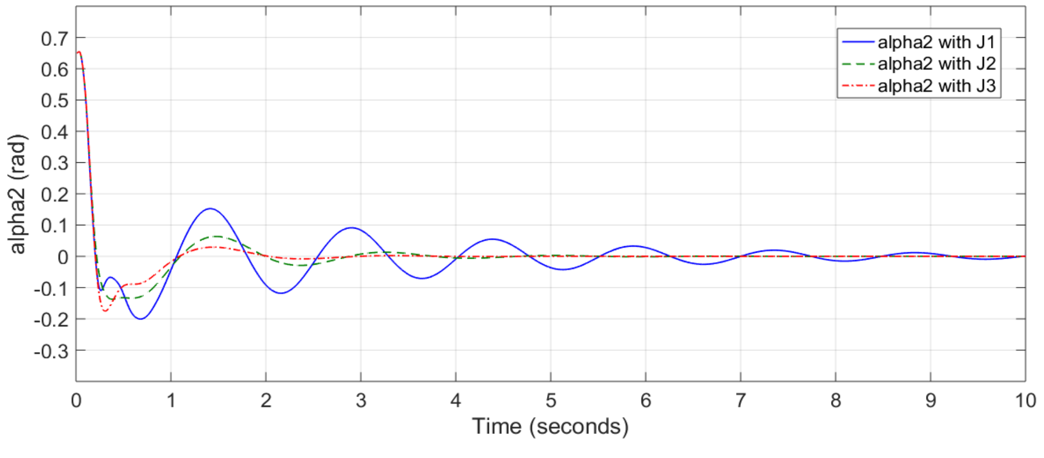


Figure 7.2: Comparison among responses of E-IP under LQR controllers through α_2 (rad)

7.2. HSM Control for E-IP System.

Consider a HSM control where the control signal is

$$u = \frac{\left(a_1 a_2 g_1 u_{eq1} + a_2 g_2 u_{eq2} + g_3 u_{eq3}\right) - \left(k_3 S_3 + \eta_3 signS_3\right)}{a_1 a_2 g_1 + a_2 g_2 + g_3} \tag{7.1}$$

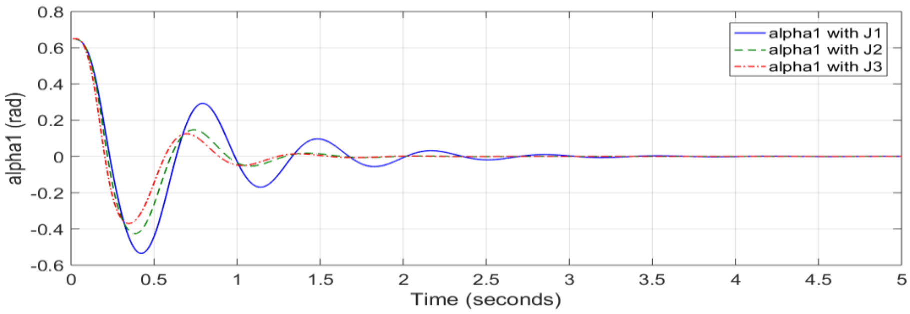


Figure 7.3: Comparison among responses of E-IP under HSM controllers through α_1 (rad)

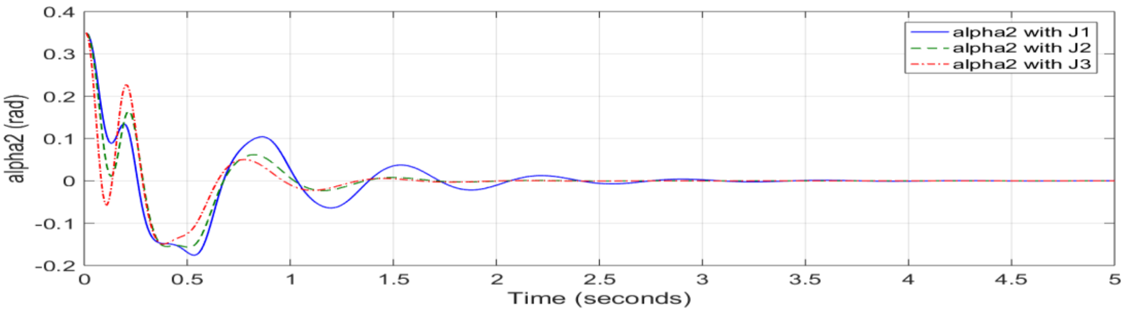


Figure 7.4: Comparison among responses of E-IP under HSM controllers through α_2 (rad)

7.3. Conventional PD Control for Two-Legged Robot.

Consider a conventional PD controllers for the motion control of AR robot.

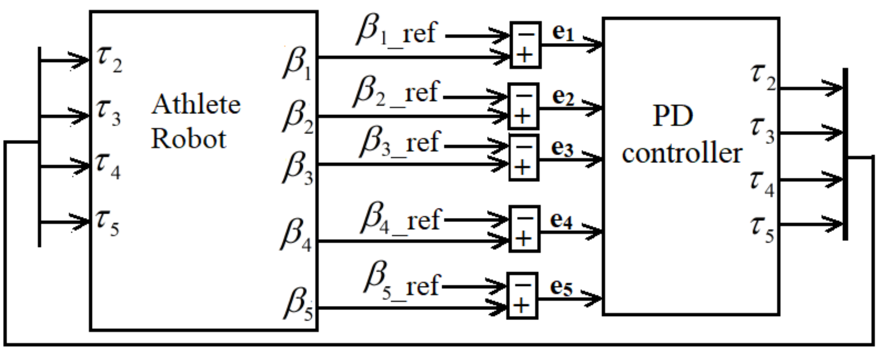


Figure 7.5**:** Structure of PID controller for step motion of AR

Simulation results of step-motion under PID controller which is described in Figure 7.5 are listed as below.

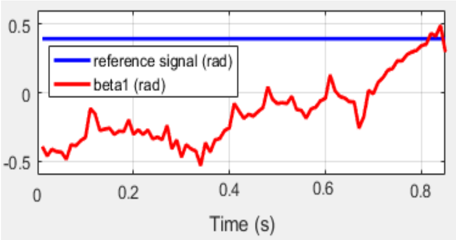


Figure 7.6: Reference signal β_{1_ref} and β_1

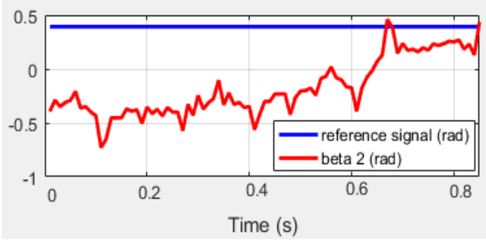


Figure 7.7: Reference signal β_{2_ref} and β_2

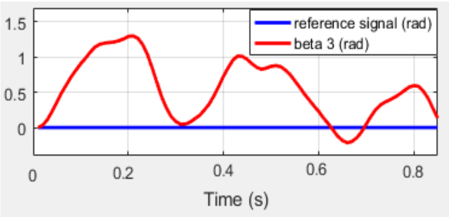


Figure 7.8: Reference signal β_{3_ref} and β_3

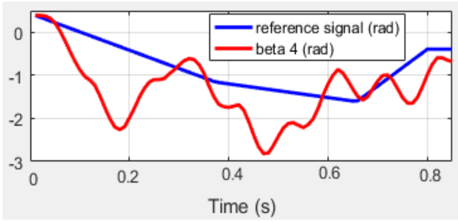


Figure 7.9: Reference signal β_{4_ref} and β_4

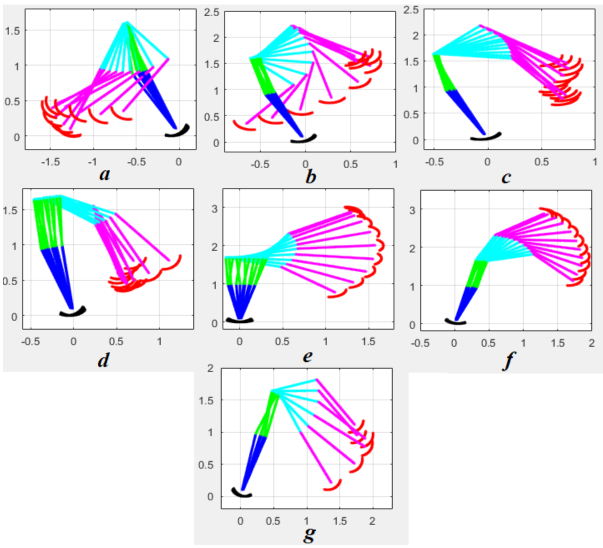
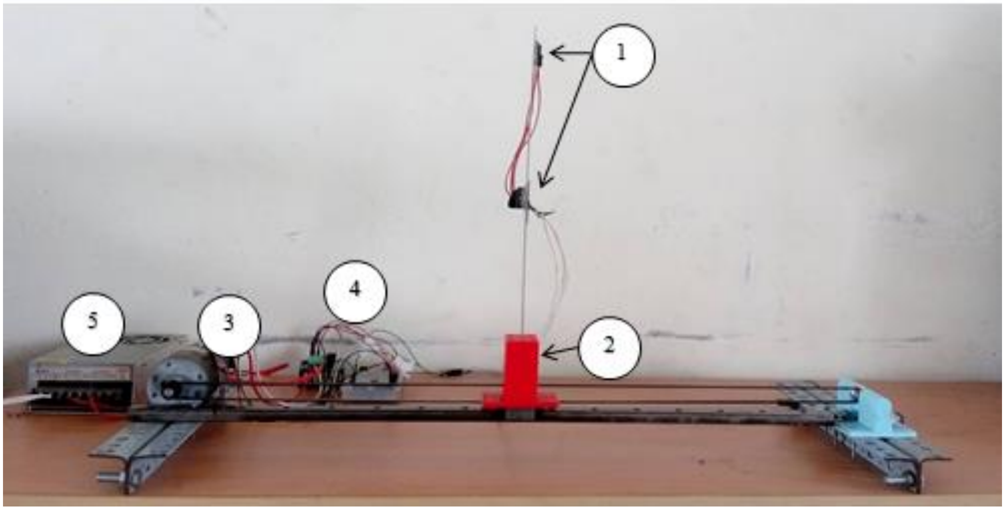


Figure 7.10**:** Motion of AR

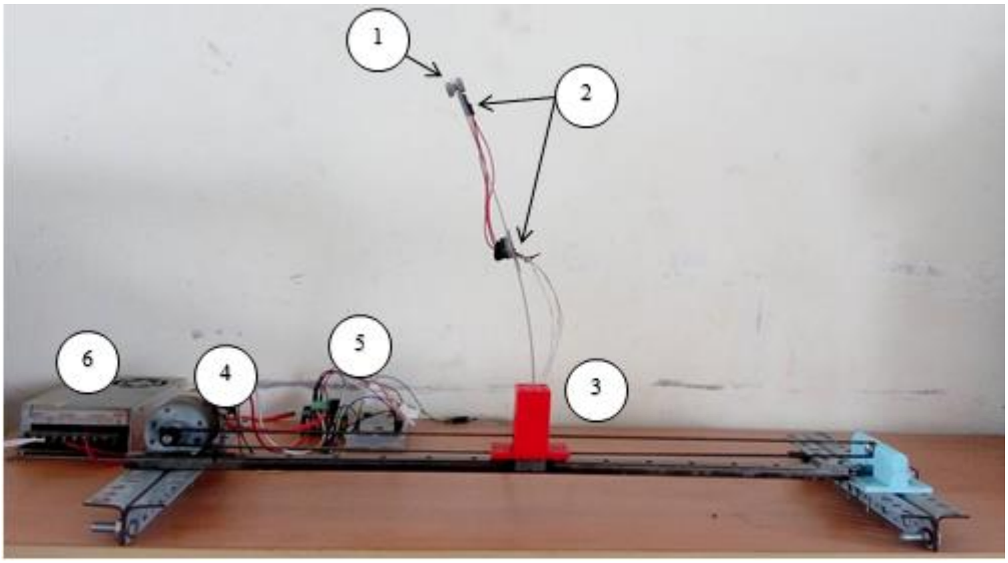
Chapter 8: EXPERIMENTAL STUDY OF MODELS WITH ELASTIC COMPONENTS

8.1. Elastic Inverted Pendulum

An experimental E-IP platform is presented in Figure 8.1 below. According to mathematical model in Figure 5.1, one MPU sensor is located at the middle of the elastic beam to measure angle α_2. Another MPU sensor is located at the top of the elastic beam to measure angle α_1



(a)



(b)

Figure 8.1: Experimental model of E-IP

8.2. Two-legged robot with Elastic legs

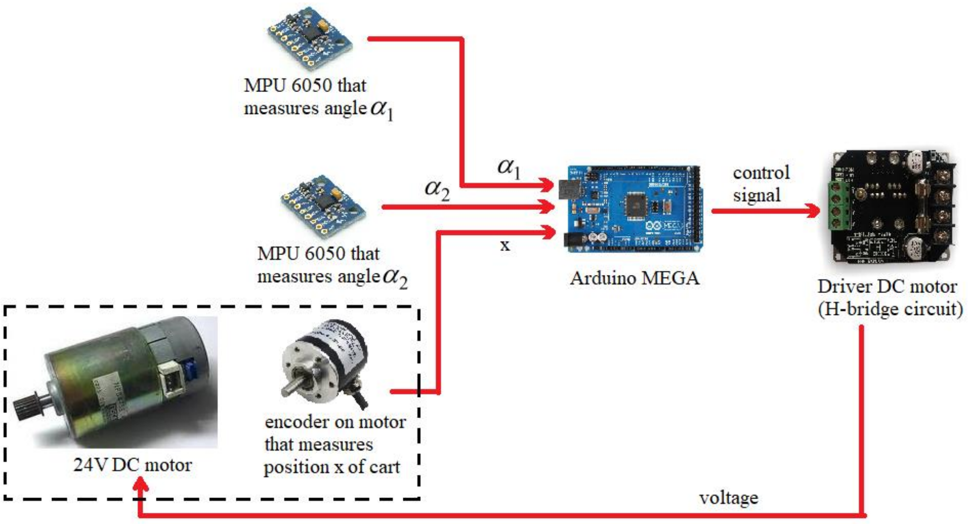


Figure 8.2: Electronics structure for E-IP model

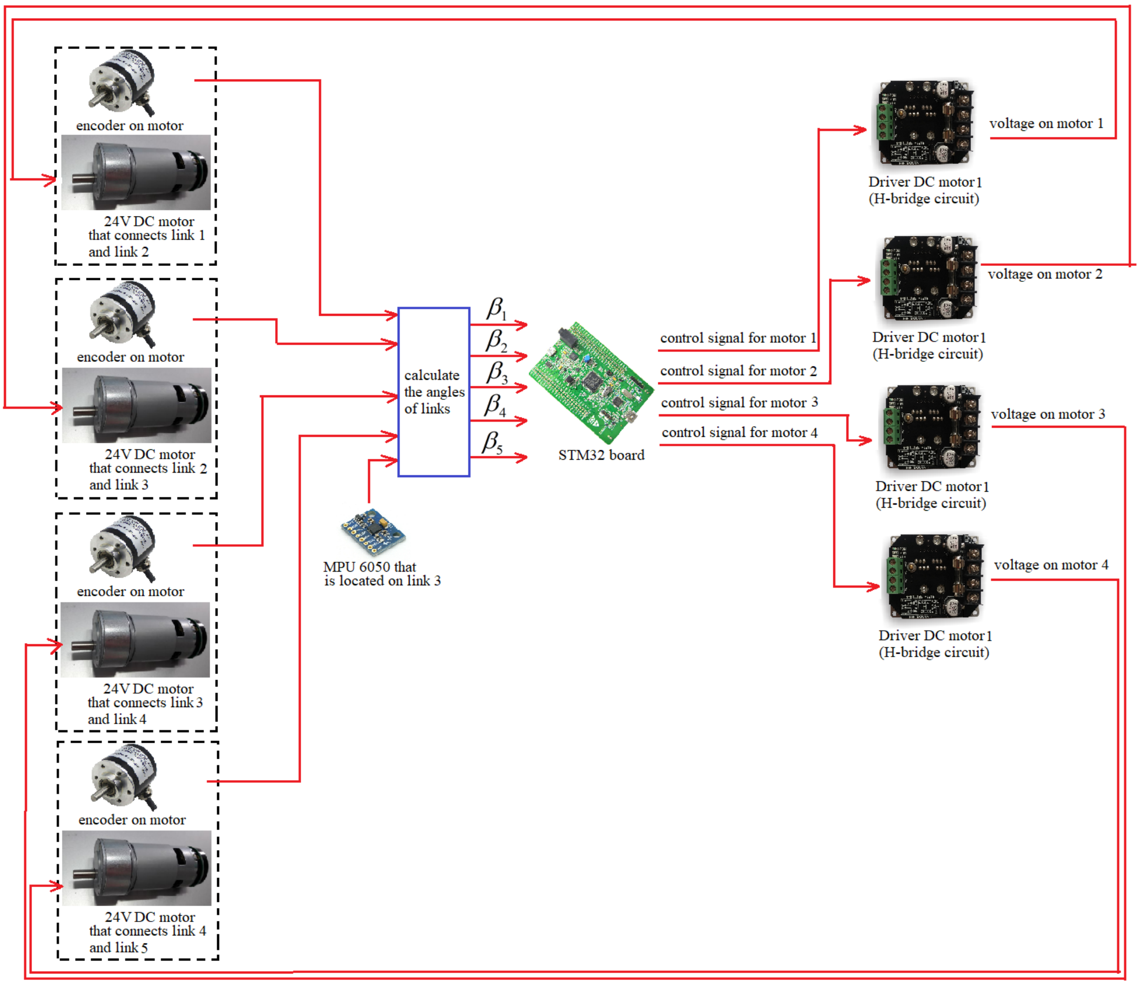


Figure 8.3: Experimental structure of AR hardware

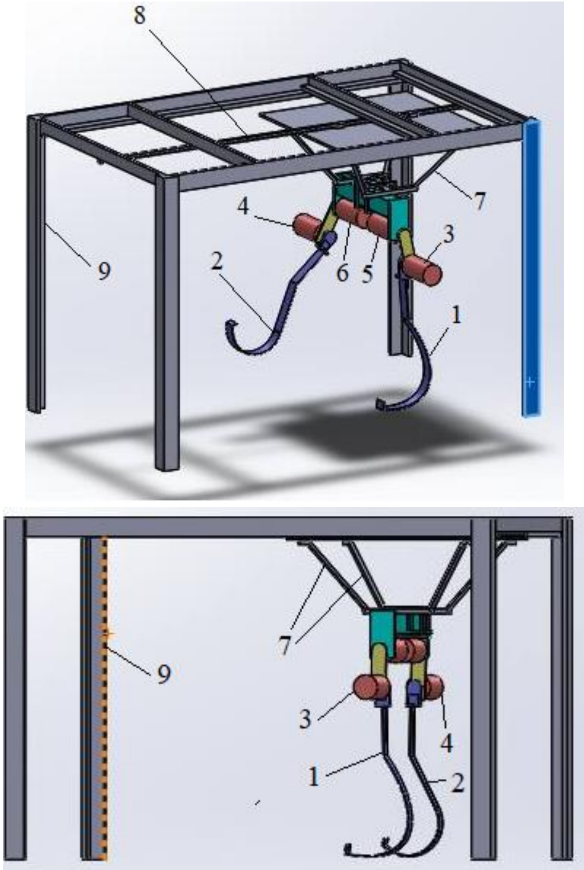


Figure 8.4: Experimental model of AR in Solidworks description

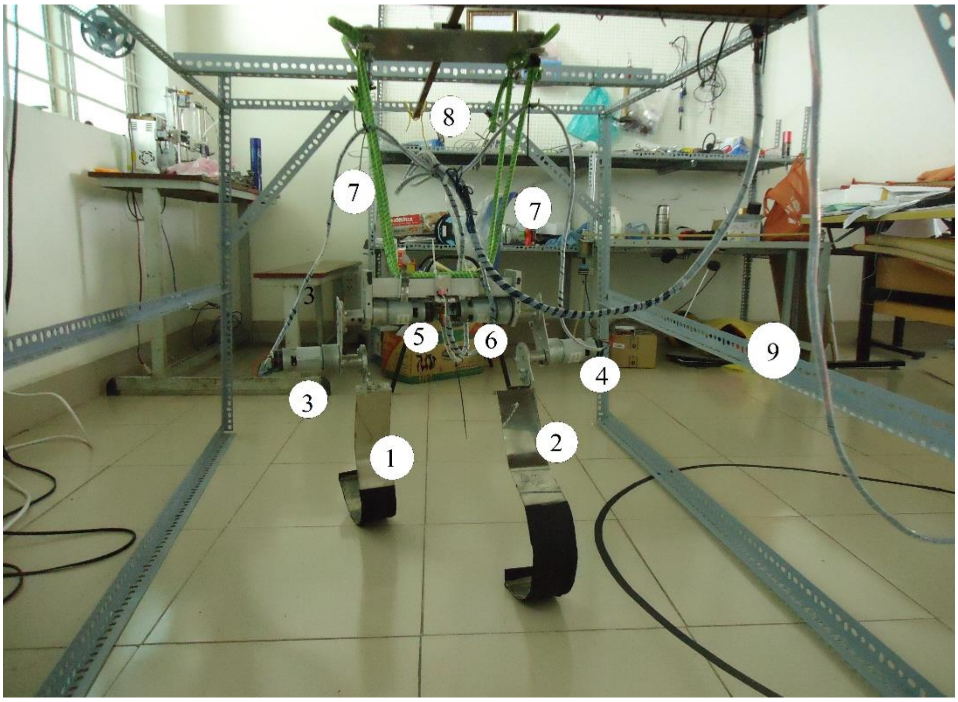


Figure 8.5: Real experimental robot in behind direction

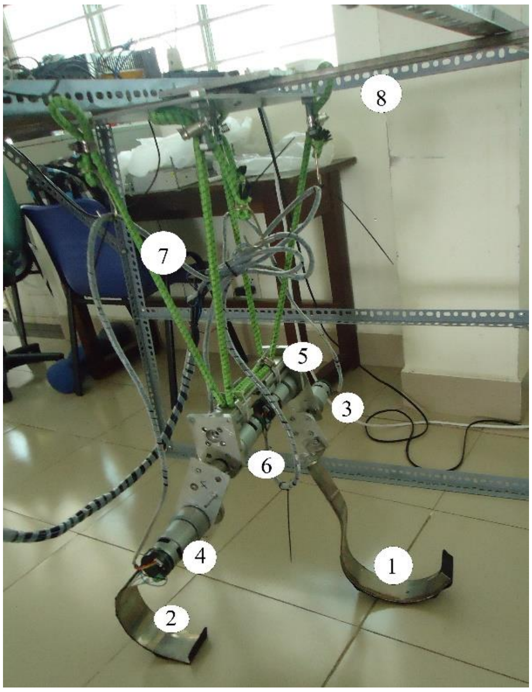
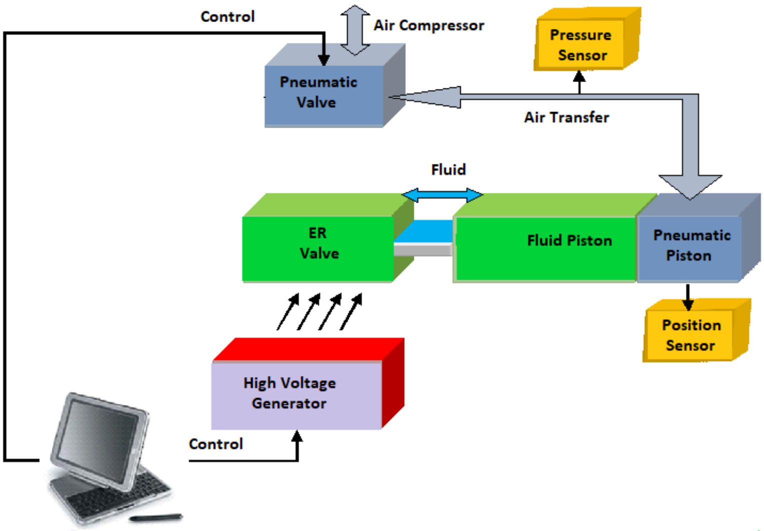


Figure 8.6: Real experimental robot in crossover direction



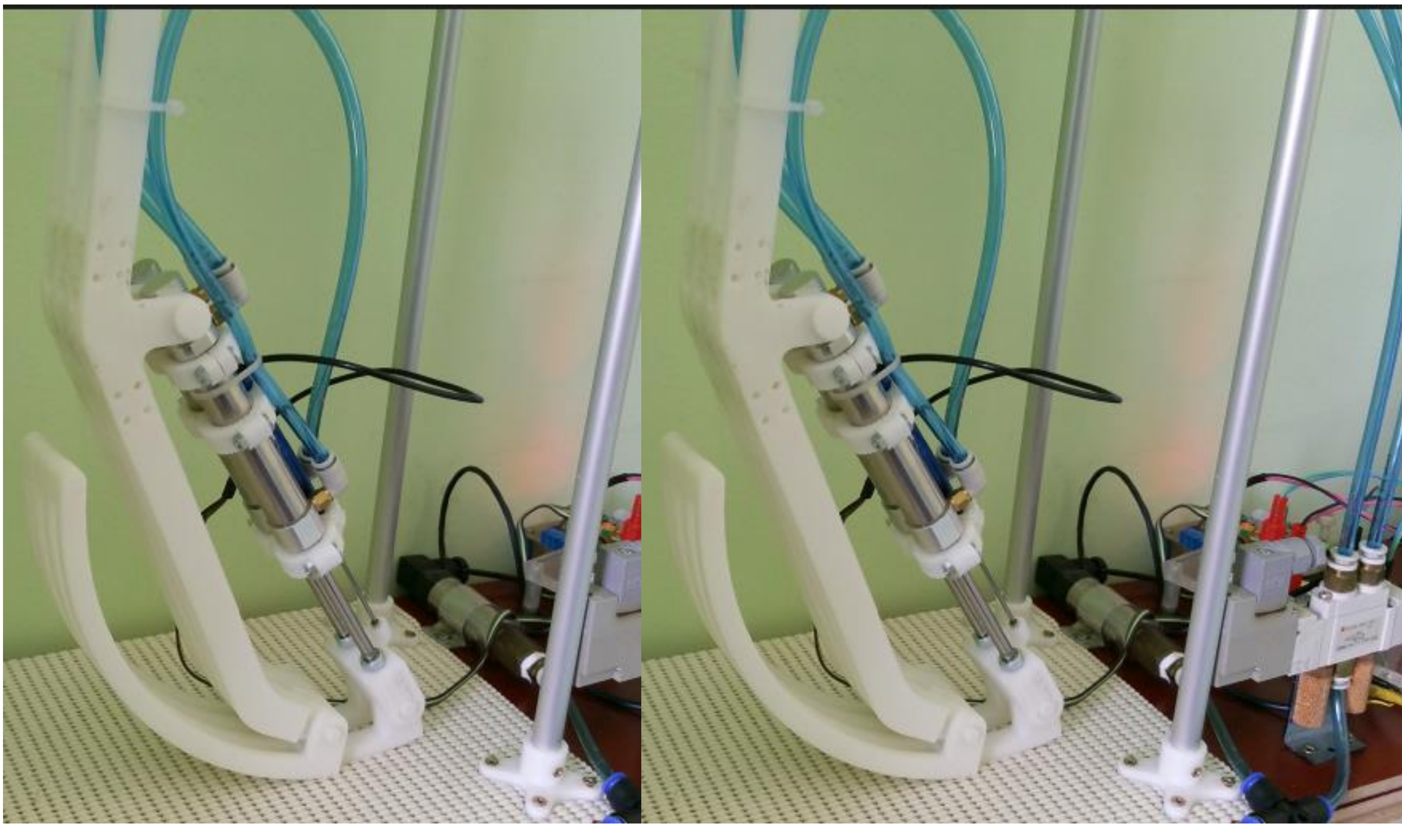


Figure 8.7: Experimental platform- mechanical architecture (Photos)

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[7] US Patent 6,302,230 Personal mobility vehicles and methods

[8] US patent 6,616,313 Motorized transport vehicle for a pedestrian

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