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Locomotion Control for Legged Robot by Virtual Contact Impedance Method

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1. Introduction

In the current infrastructure, the accessible environment is not necessarily maintained, so that it seems to be hardest for user of wheelchair (invalid chair) such as the aged and the leg-handicapped to travel in the inaccessible environment. When the user of standard wheelchair travels up/down the stairs, accompany supporter is usually needed. Therefore a single action is resultingly restricted within narrow limits. From these reasons, it is desirable to develop a mobile robot carrying the human that enables to independently travel inaccessible environment.

In the mobile hardware with the locomotive function for the stairs, the wheeled and crawler type are major (iBOT , 2010), (SUNWA , 2010). Although the wheeled type is simple and high efficient for actuating method, because of not so redundancy, degree of freedom on mobility is not so high. In addition, wheel type tends to be large size due to its multi-wheel and crawler, so that it is difficult to operate in universal inhabited space. In terms of more useful and intelligence mobility, it is necessary for the robot itself to take avoidance action automatically in order to not damage the robot itself and circumferential obstacles. So, to realize an appropriate method for avoiding the obstacle and stairs is very important issue.

In this paper, a legged mobile robot carrying the human is developed considering the adaptiveness for inaccessible environment at existing infrastructure. Although the legged robot is complex as mobile-morphology, its redundancy with multi-links is advantage to high mobility in universal space. Though earlier researches (Wu, Y. & Higuchi, M. , 2004), (Sugahara et al. , 2004), have already been reported, these are not so advanced instance that stair detection and its avoiding method are integrated. So, as a method for detecting and avoiding the stairs/obstacles, the virtual impedance control method (Tsuji & Kaneko , 1999) is proposed. This method can avoid an obstacle without contacting by receiving virtual force from virtual spring and damper installed in virtual surface region. Finally, the mobility of the legged robot by non-contacting impedance control is presented through some experiments.

2. Legged robot with linear actuators

2.1 Outline of three-legged robot

In this paper, a legged mobile robot which has the ability to carry the human is developed. The photograph of prototype model is shown in Fig.1. This robot has three legs. Each leg consists of three linear actuators, so that total degree of freedom is 9. As shown in Fig.1 and Fig.2, to maintain the rigidity, three actuators are assigned to triangular configuration and farther the part of so-called *shin* has twin screw axle mechanism that are synchronously actuated by single DC-motor. Main specification of proposed legged robot is presented in Table 1.

Width	600[mm]
Height	710∼910[mm]
Weight	35[kg]
DC motor	9ch (150[W]∼14[W])
Power supply	7.2[v] battery ×5
Sensors	3-axis accelerometer : 3ch potentiometer : 9ch sole load sensor : 12ch PSD : 2ch
Control computer	Intel(R) Pentium(R) M 1.6GHz
I/O	AD : 32ch / DA : 16ch

Table 1. Specification

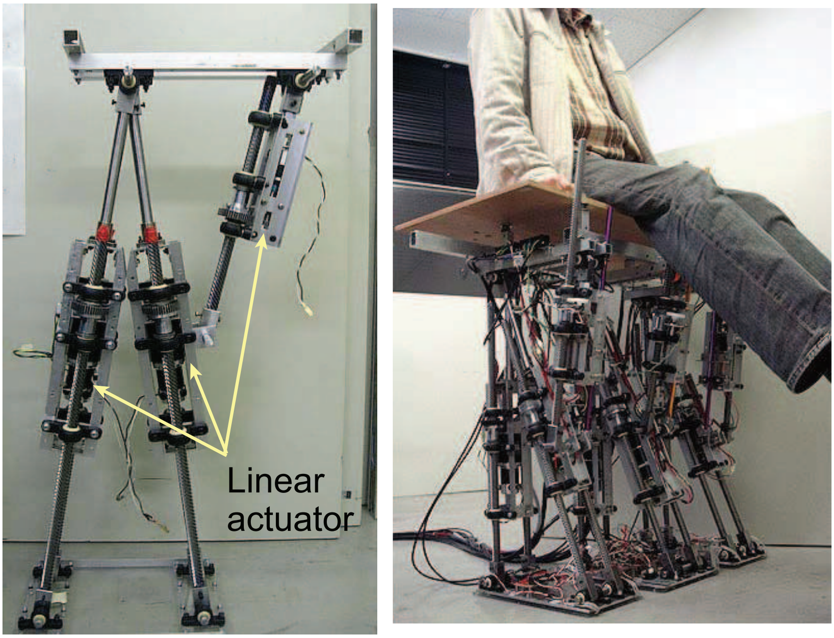


Fig. 1. Human carrying robot

2.2 Inverse kinematics

A local servo control in terms of linear actuator length is generally convenient to implement whole robot control algorithm. Then it is need to formulate the relationship between each link length and a specific position at free leg and/or at the seat. So, in this section, inverse kinematics for legged robot with linear actuated links is described.

As illustrated in Fig.3, define the heel point of grounded sole is the origin in sagittal plane and

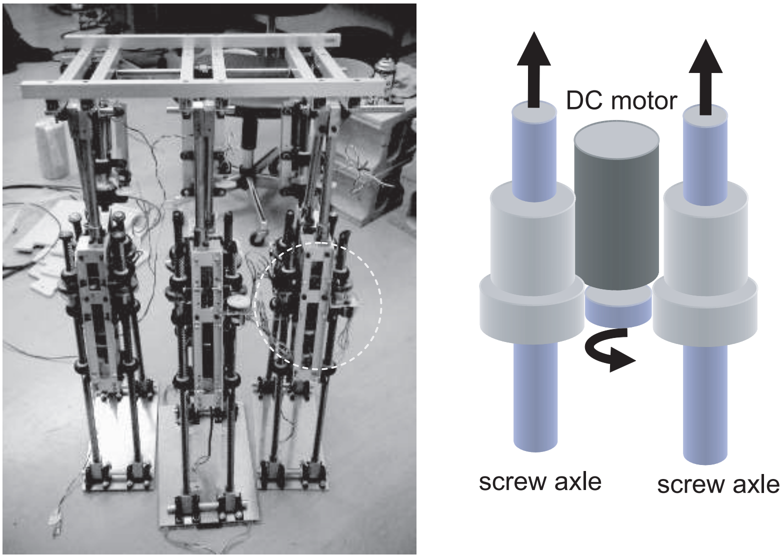


Fig. 2. Twin screw mechanism

also define $\boldsymbol{p}_t := [x_t,\ z_t,\ \delta_t]^T$ is the vector of free-leg's tip of toe and $\boldsymbol{p}_w := [x_w,\ z_w]^T$ is the vector of seat position. Farther, in Fig.3, F, W are sole and seat length, L is base length of each link and w_ε is short offset, which are all fixed.

At first, the approach to calculating link length $\boldsymbol{r}_g := [r_1^g,\ r_2^g,\ r_3^g]^T$ of the grounded leg is given. Based on geometrical structure,

$$
\begin{aligned}
r_1^g &= \sqrt{x_w^2 + z_w^2} && (1)\\
r_2^g &= \sqrt{(x_w - F)^2 + z_w^2} && (2)
\end{aligned}
$$

can be immediately calculated. From the vector equation

$$\boldsymbol{L} + \boldsymbol{w}_\varepsilon + \boldsymbol{r}_3^g = \boldsymbol{W},$$

the following procedure in terms of r_3^g is given:

$$
\begin{aligned}
\|\boldsymbol{r}_3^g\|^2 &= (\boldsymbol{W} - \boldsymbol{L} - \boldsymbol{w}_\varepsilon)^T(\boldsymbol{W} - \boldsymbol{L} - \boldsymbol{w}_\varepsilon)\\
&= W^2 + L_0^2 - 2\boldsymbol{W}^T(\boldsymbol{L} + \boldsymbol{w}_\varepsilon)\\
&= W^2 + L_0^2 - 2W(L\cos\zeta - w_\varepsilon \sin\zeta)
\end{aligned}
$$

where

$$\zeta = \tan^{-1}\frac{-z_w}{F - x_w}. \tag{3}$$

As a result we obtain

$$\boldsymbol{r}_3^g = \sqrt{W^2 + L_0^2 - 2W(L\cos\zeta - w_\varepsilon \sin\zeta)}. \tag{4}$$

Next, link length $\boldsymbol{r}_f := [r_1^f,\ r_2^f,\ r_3^f]^T$ of free leg also can be given by similar approach. The followings are resultingly obtained:

$$\begin{aligned} r_1^f &= \sqrt{(\boldsymbol{p}_t - \boldsymbol{F} - \boldsymbol{p}_w)^T(\boldsymbol{p}_t - \boldsymbol{F} - \boldsymbol{p}_w)} && (5) \\ &= \sqrt{(x_t - F\cos\delta_t - x_w)^2 + (z_t - F\sin\delta_t - z_w)^2} \\ \boldsymbol{r}_2^f &= \sqrt{(x_w - x_t)^2 + (z_w - z_t)^2} && (6) \\ \boldsymbol{r}_3^f &= \sqrt{W^2 + L_0^2 - 2W(L\cos\phi - w_\varepsilon \sin\phi)} && (7) \end{aligned}$$

where

$$\phi = \tan^{-1}\frac{z_t - z_w}{x_t - x_w}. \tag{8}$$

According to above proceeding, if the kinematics in terms of positional vector is represented by

$$\begin{bmatrix} \boldsymbol{p}_w \\ \\ \boldsymbol{p}_t \end{bmatrix} = \boldsymbol{f}(\boldsymbol{r}_g, \boldsymbol{r}_f) = \begin{bmatrix} \boldsymbol{f}^w(\boldsymbol{r}_g) \\ \\ \boldsymbol{f}^t(\boldsymbol{r}_g, \boldsymbol{r}_f) \end{bmatrix},$$

then we define the inverse kinematics explicitly solving all links length as

$$\begin{bmatrix} \boldsymbol{r}_g \\ \\ \boldsymbol{r}_f \end{bmatrix} = \boldsymbol{f}^{-1}(\boldsymbol{p}_w, \boldsymbol{p}_t) = \begin{bmatrix} \boldsymbol{f}_g^{-1}(\boldsymbol{p}_w) \\ \\ \boldsymbol{f}_f^{-1}(\boldsymbol{p}_w, \boldsymbol{p}_t) \end{bmatrix}.$$

3. Control strategy for advanced mobility

3.1 Non-contact impedance method

In the case where mobile robot is used in public facility and the home environment, in order to not damage the robot itself and environmental objects, it is necessary to take into account for interactive force between end-effector and circumstance. Impedance control is often used for such control method that makes robot's end-effector have desired force and realizes mechanical compliance.

In a general way, the realization of impedance control necessitates a certain contact with external objects. For safety's sake, however, it is desirable for mobile robot to avoid obstacles without contacting external objects. From these reasons, this paper proposes a method of avoiding obstacles by non-contact impedance control.

The concept of non-contact impedance control is illustrated in Fig.4. Assume that virtual contact force occurs via virtual spring and damper, if an obstacle trespasses on virtual surface postulated at the tip of a toe. Assume $\boldsymbol{\xi} := [\xi_x,\ \xi_z]^T$ to be trespassing vector on virtual surface, virtual contact force is given by

$$\boldsymbol{u}_v = \begin{cases} \boldsymbol{J}^T(\boldsymbol{r}_f)(\boldsymbol{D}_v\dot{\boldsymbol{\xi}} + \boldsymbol{K}_v\boldsymbol{\xi}) & (\boldsymbol{\xi} < 0) \\ \boldsymbol{0} & (\boldsymbol{\xi} \geq 0) \end{cases} \tag{9}$$

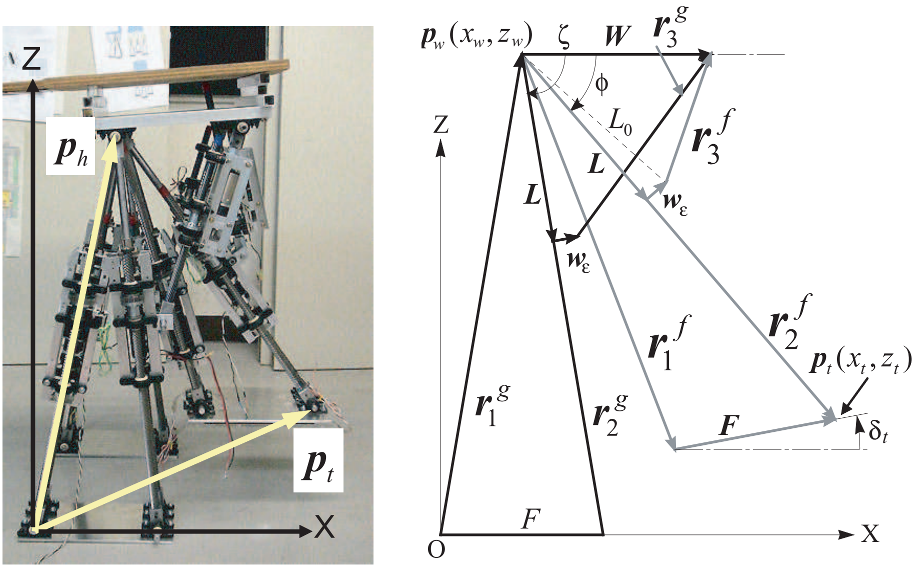


Fig. 3. Linear actuated legs configuration

here, $\boldsymbol{K}_v$, $\boldsymbol{D}_v$ are virtual spring and viscosity coefficient matrix respectively. $\boldsymbol{J}(\boldsymbol{r}_f)$ is Jacobian-matrix defined by

$$\boldsymbol{J}(\boldsymbol{r}_f) = \begin{bmatrix} \frac{\partial f_1^t}{\partial r_1^f} & \frac{\partial f_1^t}{\partial r_2^f} & \frac{\partial f_1^t}{\partial r_3^f} \\ \frac{\partial f_2^t}{\partial r_1^f} & \frac{\partial f_2^t}{\partial r_2^f} & \frac{\partial f_2^t}{\partial r_3^f} \end{bmatrix}. \tag{10}$$

In actual robot control, virtual surface can be formed in realtime by measuring the distance between obstacle and end-effector using position sensitive detector (PSD).

3.2 Control method

The ideal task of mobile robot is to realize intelligent behavior robustly even if planed reference path is obstructed by irregular pitch steps or wall projection. As mentioned above section, our control strategy combines tracking control for planed reference path with force control by virtual contact impedance.

The proposed control method, as shown in Fig.5, consists of three control law Eq.(11), which are reference trajectory control $\boldsymbol{u}_t$, virtual contact control $\boldsymbol{u}_v$ and sole counter force control $\boldsymbol{u}_s$.

$$\boldsymbol{u} = \boldsymbol{u}_t + \boldsymbol{u}_s + \boldsymbol{u}_v \tag{11}$$

$\boldsymbol{u}_t$ is determined by servo control loop for reference trajectories in terms of links length which are precedently given to realize a walking pattern. $\boldsymbol{u}_s$ is used to compensate the gap between the sole and the floor if the robot does not poise owing to the transition of center of mass, external force, etc.

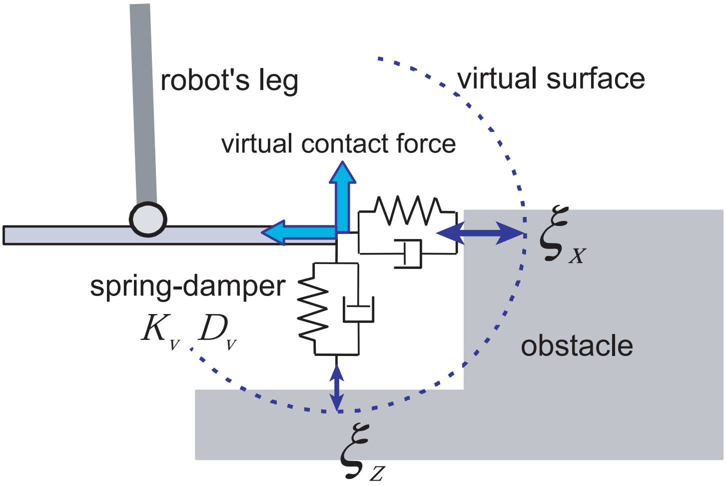


Fig. 4. Concept of non-contact impedance control

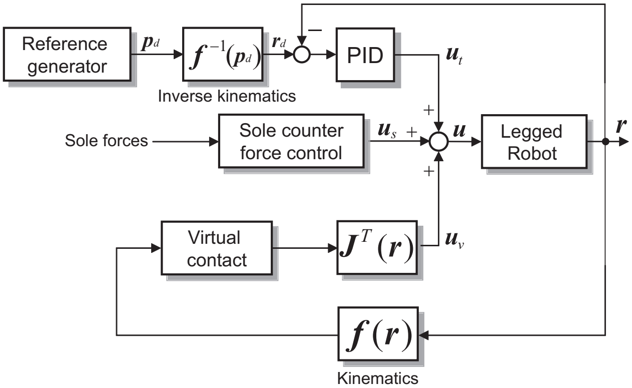


Fig. 5. Control system

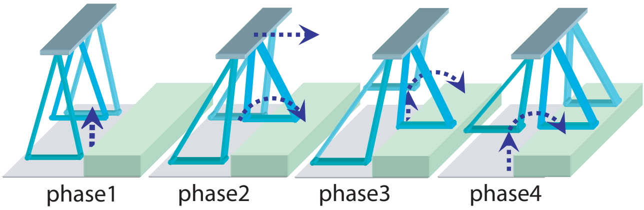


Fig. 6. Walking sequence

3.3 Walking pattern

In order to make the mobile robot proceed to a certain direction, some locomotion pattern is needed beforehand. Then it is useful to generate corresponding trajectories along the locomotion pattern in realtime and to realize feedback control for such trajectories.

A human carrying robot proposed in this paper must be able to move three legs individually in consideration of high mobility and stability. This paper considers the gait in which a single leg travels for free-leg and the other two legs keep on standing as fundamental walking pattern. Since such gait can posture robot's center of mass inside polygonal area formed by ground soles, static walk becomes to practicable. Each phase in proposed walking pattern, as illustrated in Fig. 6, is briefly explained as follows:

phase-1 : As swing up center leg, detect the edge of step based on the degree of change of PSD value. At the same time compute the height of step by downward PSD.

phase-2 : Give a reference elliptical orbit in order that for free sole to land on the step. Then give a horizontal orbit for seat position in keeping current height.

phase-3 : Swing left leg up to step height (which has already been given at phase-1. And give a reference elliptical orbit in order that for its sole to land on the step.

phase-4 : For right leg, give same operation as phase-3.

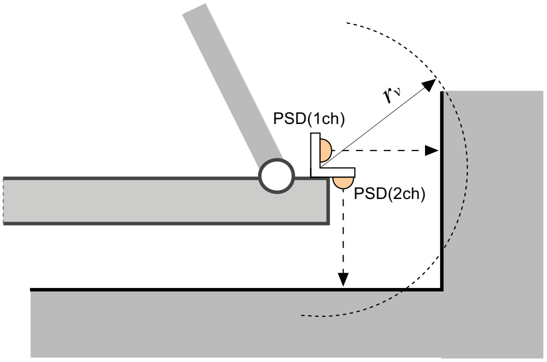


Fig. 7. Location of PSD

4. Experiment

4.1 Walking up stair

An experiment to avoid a stair installed in front of the robot is tried. In this experiment, while the distance between robot and stair can be measured by PSD in real time and the radius of virtual surface is given as $r_v = 5$ [cm], notice that the height of stair is unknown to human. Fig. 7 shows the location of 2ch PSD assigned for virtical and horizontal measures.

Fig. 8 presents sequential motion captures in walking up a stair, where a man with about 50[kg] weight is embarking on the seat. Indeed, because the robot travels in constantly standing by two legs, it is confirmed that the behavior of the robot loading a human is stable. Fig. 9(b) shows trajectories and virtual force at tip of toe, where dashed line means reference trajectory planned at phase-1, phase-2 in walking pattern. For comparison, the trajectory without virtual contact control is also shown in Fig. 9(a). As shown in Fig. 9, it is found that as tip of toe approaches edge of stair closer, virtual force increases by virtual contact efficiency. Consequently it is confirmed that proposed virtual contact method can avoid the obstacle even if reference trajectory which approaches obstacle closely is applied.

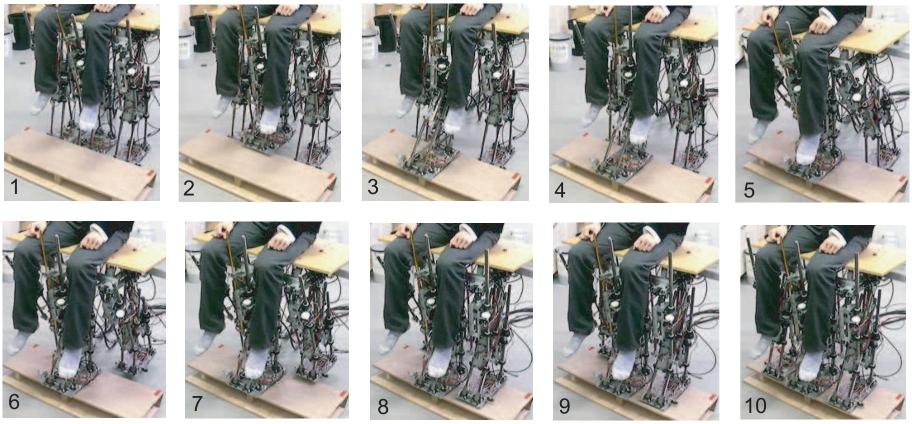
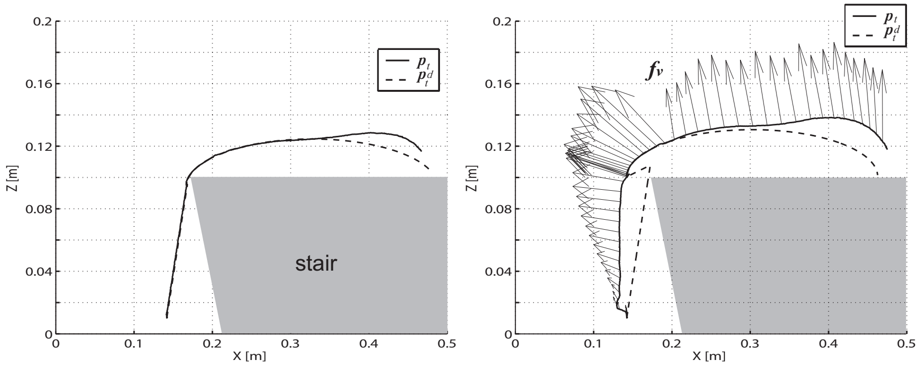


Fig. 8. Sequential motion captures



(a) without Virtual contact control (b) with Virtual contact control

Fig. 9. Trajectory and virtual force at tip of toe

4.2 Soft landing

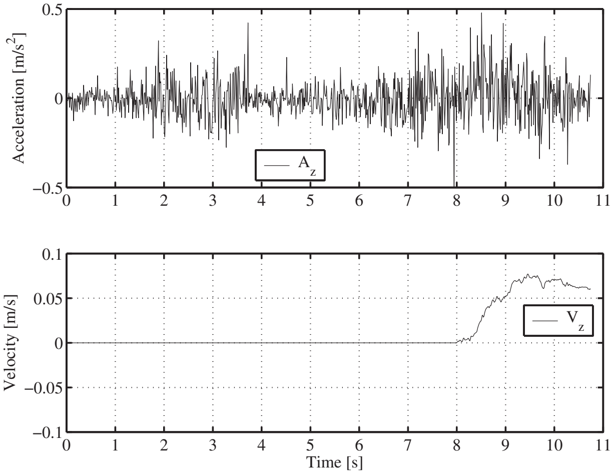
The efficiency that alleviate the robot's impact in landing, i.e. soft-landing is expected by applying a variable gain $\boldsymbol{\alpha}$ to control law

$$\boldsymbol{u} = \boldsymbol{\alpha}\boldsymbol{u}_t + (I - \boldsymbol{\alpha})\boldsymbol{u}_v + \boldsymbol{u}_s \quad (0 < \alpha_i < 1)\,. \tag{12}$$

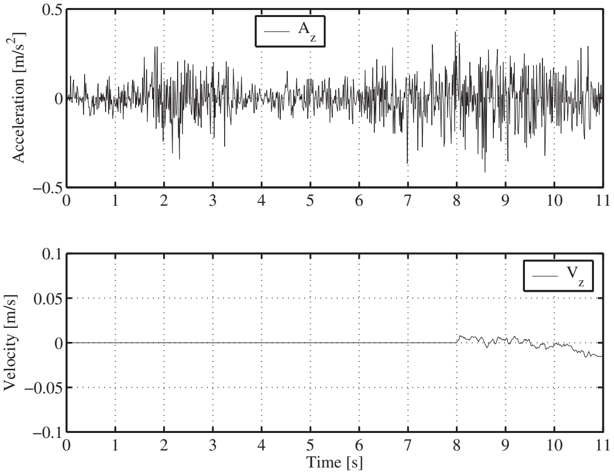
Then, as second experiment, we verify the efficiency of soft-landing by measuring the degree of pitch in landing phase. Fig. 10(a) shows vertical acceleration and velocity at the seat when $\boldsymbol{\alpha} = I$, while Fig. 10(b) shows same datum when virtical contact control is given by

$$\boldsymbol{\alpha} = \mathrm{diag}\{0.15,\ \ 0.25\}$$

in trial and error. Obviously the degree of pitch controlled by virtual contact is more suppressed than the case not controlled. As a result, it is expected that mechanical landing impact and the fearfulness for the passenger are alleviated.



(a) without Virtual contact control



(b) with Virtual contact control

Fig. 10. Degree of pitch at the seat

5. Conclusion

In this paper, we have developed three-legged mobile robot which has the ability to carry the human by using has 9 linear actuated links. Each leg consists of three linear actuators assigned to triangular configuration in order to maintain the rigidity. For such linear structure, the inverse kinematics has been given. The inverse kinematics for local servo control is also given. As a method for avoiding the obstacles, we have proposed the virtual impedance control method which can avoid the stairs without contacting by receiving virtual force from virtual spring and damper installed in virtual surface region. Finally, the mobility for avoiding unknown height step and soft-landing motion have been confirmed through some experiments.

6. References

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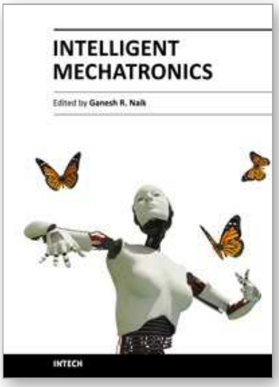

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This book is intended for both mechanical and electronics engineers (researchers and graduate students) who wish to get some training in smart electronics devices embedded in mechanical systems. The book is partly a textbook and partly a monograph. It is a textbook as it provides a focused interdisciplinary experience for undergraduates that encompass important elements from traditional courses as well as contemporary developments in Mechtronics. It is simultaneously a monograph because it presents several new results and ideas and further developments and explanation of existing algorithms which are brought together and published in the book for the first time.

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