Paper:

Experimental Identification of Manipulator Dynamics Through the Minimization of its Natural Oscillations

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This work presents a method of identifying the dynamics parameters of rigid-body manipulators through the minimization of its natural oscillations. It is assumed that each link has an actuated joint that is different from its center of mass, such that its driving torque is influenced by gravitational force. In this earlier results of our study, it is assumed that the inertias can be expressed in terms of the mass and center of mass. This work utilizes the actual force of gravity for the manipulator link to achieve natural oscillation. The oscillatory motion allows the system to be converted into an optimization problem through the minimization of the frequency of oscillation. The correct dynamics parameters are found when the minimum frequency of oscillation is achieved. The proposed method is analyzed and a theorem is presented that supports the claims presented in this work together with implementation results.

Keywords: dynamics identification, experimental method, optimization, natural oscillation

1. Introduction

The absence of a direct procedure to identify the full dynamic parameters of multi-linked bodies remains one of the major challenges in achieving full dynamics control of manipulators. This is especially true as the degrees of freedom of manipulators increase as in the case of humanoid robots. Earlier work on manipulator arms that attempted to identify their dynamic parameters include the inertial parameters of the Asada Direct Drive arm determined by the use of batch least squared error parameter estimation [1], adaptive control with on-line dynamics identification on the Adept 1 arm [2], and an experiment that was dependent on the condition number of the persistent excitation matrix and to optimize this condition number using the calculus of variations [3]. More recent identification procedures of manipulator arm dynamics include the use of torque data [4], floating-base motion dynamics [5], iterative learning [6], neural network aided identification [7], set membership uncertainty [8], and simultaneous identification and control [9]. Identification procedures that are more robot specific include [10–13]. Some examples of identification procedures for humanoid robot dynamics used neural network [14], and fuzzy-stochastic functor machine [15].

A successful dynamics identification [16] and implementation on a mobile manipulator tasked to perform an aircraft canopy polishing [17] is one of the few successful implementations on full dynamics manipulator control. The method of identification is based on the oscillatory motion of each link, with the dynamics parameters treated as lumped models. Because a the derivation of a simplified symbolic model can be very computationally tasking, especially for higher degrees of freedom robot, the identification procedure presented in [17] becomes impractical to implement in humanoid robots.

The contribution of this work lies in the identification of each of the individual dynamics parameters, and not of the lumped models. This method of dynamics identification will become more practical to implement with the higher degrees of freedom manipulators like a humanoid. The experimental procedure will let each link of the manipulator achieve natural oscillation. Once this is achieved, the method now now becomes an optimization computation with an objective to minimize the frequency of oscillation. A higher frequency of oscillation reflects an overcompensation of the dynamics parameters, while an under compensation will make the system drop due to the gravitational force. The correct mass, center of mass, and inertial parameters correspond to the least frequency of oscillation given an initial perturbation from equilibrium. This work on dynamics parameters modeling and identification can be further extended to humanoid object manipulation [18] and motion planning [19–22] to be used in our laboratory for the robot soccer competition. Some strategies on humanoid robot modeling and control include fuzzy neural network [23], global dynamics [24], and ground interaction control [25].

2. Overview

2.1. An Inverted Pendulum

The sum of the kinetic energy K and potential energy P of an upright pendulum, as shown in **Fig. 1**, consisting of a slender bar with mass m and length l is

$$K - P = \frac{1}{2}\left(\frac{1}{3}ml^2\right)\left(\frac{d\theta}{dt}\right)^2 - \frac{1}{2}mgl\cos\theta \quad . \quad . \quad (1)$$

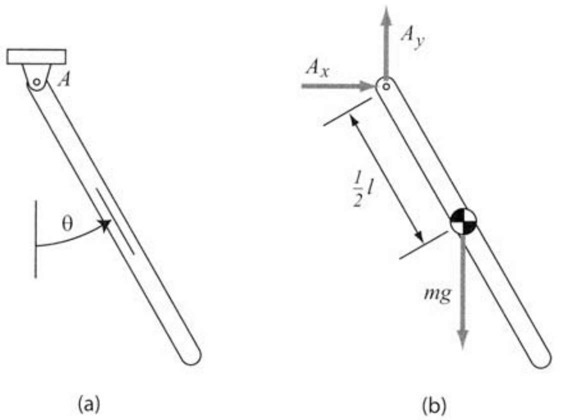

Fig. 1. Subfigure(a) shows an upright pendulum turning about point A due to gravity and an initial displacement from equilibrium position. Subfigure(b) shows the free body diagram.

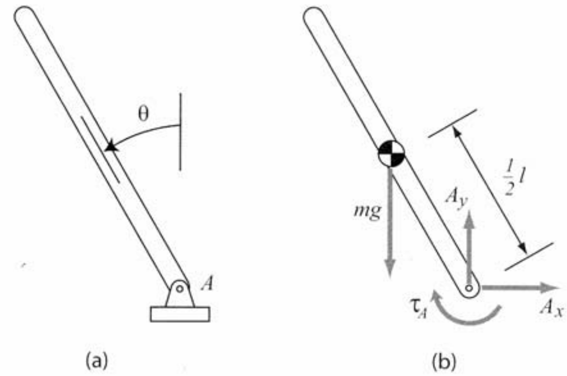

Fig. 2. Subfigure(a) shows an inverted pendulum. Subfigure(b) shows the free body diagram such that the gravitational compensation is sent to the system all the time which results into a system that is floating against gravity.

and is constant, where g is the gravitational constant and θ is the angular displacement from the vertical axis. Taking the time derivative and assuming small angular displacements, the above equation can be expressed as

$$\frac{d^2\theta}{dt^2} + \frac{3g}{2l}\theta = 0 \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

with constant frequency of oscillation $\omega^2 = 3g/2l$. This relationship shows the frequency of oscillation being dependent on the physical characteristic of the pendulum. Thus a different pendulum with different physical characteristics will give a different value of the frequency of oscillation. With no torque given at point A, the only moment acting on the pendulum is that due to gravity. Given an initial displacement, this moment will cause the system to respond with angular acceleration and achieve natural oscillation.

Next we consider and inverted pendulum as shown in **Fig. 2**. This time, a torque τ_A is given at point A as shown in the free-body diagram of Subfigure (b). With the torque sent to the system that is equal to the moment due to gravity, the inverted pendulum will now "float" against gravity. When an initial push is given, the inverted pendulum will achieve angular acceleration such that the effective torque sent to the system is

$$\tau_A = \left(\frac{1}{3}ml^2\right)\ddot{\theta} + \frac{1}{2}mgl\sin\theta. \quad \ldots\ldots \quad (3)$$

That is, the effective torque sent at point A is the difference (or sum) between the given initial push that resulted into an acceleration and the moment due to gravity. The difference will vary depending on the value of the angular displacement of the inverted pendulum. This created a spring-like toque at point A and resulted in a natural oscillation of the inverted pendulum.

2.2. The Frequency of Oscillation

The value of the gravitational compensation torque that is sent to the manipulator will depend on the values of the dynamics parameters model. When this torque is applied, and an initial disturbance from rest is given to the manipulator, it will result into a manipulator achieving a certain frequency of oscillation. Higher values used in the dynamics model will result into a higher frequency of oscillation due to bigger torque sent to the pendulum. Lower values of these parameters will result into a system moving at a lower frequency of oscillation. Much lower values can possibly result into a manipulator falling due to gravitational force. In this dynamics parameter identification, it is the actual force of gravity that is being utilized to define the critical boundary for the identification of the correct values of the dynamics parameters. The main objective is to minimize the frequency of oscillation such that the dynamics parameters are not overcompensated which results into higher frequency of oscillation or under compensated which results into a system falling under gravitational force. By doing this, the problem becomes an optimization problem with an objective function

$$\min \omega(I, m, r) \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

where ω is the frequency of oscillation that is a function of inertia I, mass m, and center of mass r. The above equation is for the general case where the dynamics parameters are dependent on inertia, mass, and center of mass.

2.3. Multi-Linked Rigid Body Dynamics

The general case of the multi-linked rigid body dynamics of a manipulator will be presented. The torque to be sent to each joint of the robot is computed by taking the kinetic energy K and potential energy P and solving the Lagrange equation of $L = K - P$ [26]

$$\frac{d}{dt}\left[\frac{\partial L}{\partial \dot{q}_i}\right] - \frac{\partial L}{\partial q_i} = \tau_i \quad \ldots\ldots\ldots\ldots \quad (5)$$

such the joint torque vector is expressed as

$$\tau = \mathbf{A}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}). \quad \ldots\ldots\ldots \quad (6)$$

The symbol $\mathbf{A}(\mathbf{q})$ is the joint-space inertia matrix, $\mathbf{c}(\mathbf{q}, \dot{\mathbf{q}})$ is the Coriolis and centrifugal forces vector, $\mathbf{g}(\mathbf{q})$ is the gravitational terms vector, and $\ddot{\mathbf{q}}, \dot{\mathbf{q}}, \mathbf{q}$ are the joint space acceleration, velocity, and displacement. The control equation is given as

$$\ddot{\mathbf{q}} = \ddot{\mathbf{q}}_d - \mathbf{k}_v(\dot{\mathbf{q}} - \dot{\mathbf{q}}_d) - \mathbf{k}_p(\mathbf{q} - \mathbf{q}_d) \quad \dots\dots \quad (7)$$

where the proportional $\mathbf{k}_p$ and derivative $\mathbf{k}_v$ gains are set to zero, and the desired acceleration $\ddot{\mathbf{q}}_d$ is set to zero as well. This makes an open-loop system and subsequently, the first term of Eq. (6) equals to zero. The torque sent to the manipulator joints would be the Coriolis and centrifugal forces and the gravitational terms. The general case of multi-linked rigid body now becomes the same as the one link with the added Coriolis and centrifugal forces, which initially is equal to zero when the system is at rest. When the system is given an initial push, the total effective torque includes that due to acceleration $\ddot{\mathbf{q}}$, the gravitational forces, and the Coriolis and centrifugal forces which are now active because the joint velocities are nonzero.

In the experimental procedure presented in this work, $\ddot{\mathbf{q}}$ of the control Eq. (7) is always zero so the terms in $\mathbf{A}(\mathbf{q})$ of Eq. (6) cannot be identified. To address this, the method proposed in this work will express the inertia terms in terms of mass and center of mass, which are identified through the gravitational terms model. This approach can be sufficient in most cases considering that the link design in most manipulators are symmetric. The inertia model to use in expressing it in terms of mass and center of mass can be derived based on the geometry of the manipulator links.

3. The Proposed Dynamics Identification Method

In this section we will show a mathematical proof of the proposed method to support the claims in this work in identifying mass, center of mass, and moment of inertia. In addition, corresponding algorithms will be shown.

Given a physical system such that each link is influenced by gravitational force, the dynamics parameters can be identified by letting the system achieve natural oscillation through the force of gravity. It is assumed that the links move at small angular displacements around $\pm 15°$ away from zero gravity axis. Friction contribution is disregarded in this work and will be addressed in the future. A symbol $\tilde{\square}$ on a physical system denotes its approximation.

Theorem 1: A multi-link rigid manipulator with revolute joints is under torque control and is influenced by gravitational force. Its minimum frequency of oscillation ω is achieved when the estimated physical parameter values in the mathematical model are closest to the values in the physical system.

Proof:

Case I. Single Degree-of-Freedom. Equating the torque between the physical system and the mathematical model results in

$$\tau = I\ddot{\theta} + g(\theta) = \tilde{I}u + \tilde{g}(\theta) \quad \dots\dots\dots \quad (8)$$

where the control equation $u = \ddot{\theta}_d - k_v(\dot{\theta} - \dot{\theta}_d) - k_p(\theta - \theta_d)$. Setting $u = 0$ results into open-loop control such that

$$\ddot{\theta} + \frac{g(\theta) - \tilde{g}(\theta)}{I} = 0. \quad \dots\dots\dots \quad (9)$$

Because of relatively small angular displacements, Eq. (9) can be considered as an undamped linear second-order system [27] where

$$\omega^2 = f(g(\theta) - \tilde{g}(\theta)). \quad \dots\dots\dots \quad (10)$$

Because I is constant, ω is minimum when $g(\theta) = \tilde{g}(\theta)$.

Case II. Multiple Degree-of-Freedom. The torques sent to the physical system and the mathematical model are equal and can be expressed as,

$$\begin{aligned}\tau &= \mathbf{A}(\theta)\ddot{\theta} + \mathbf{c}(\theta, \dot{\theta}) + \mathbf{g}(\theta) \\ &= \tilde{\mathbf{A}}(\theta)\mathbf{u} + \tilde{\mathbf{c}}(\theta, \dot{\theta}) + \tilde{\mathbf{g}}(\theta). \quad \dots\dots \quad (11)\end{aligned}$$

With relatively small joint velocities, Coriolis and centrifugal forces are less dominant and are ignored. With small angular displacements, gravitational terms can be considered linear. Setting the control equation $\mathbf{u} = \mathbf{0}$ results into

$$\ddot{\theta} + \mathbf{A}(\theta)^{-1}[(\mathbf{g}(\theta) - \tilde{\mathbf{g}}(\theta))]. \quad \dots\dots \quad (12)$$

With the small angular displacement $\mathbf{A}(\theta)$ can be considered constant. As the correct parameter values are approached, the system becomes decoupled such that each link can be independently considered as second-order undamped linear system [27] where

$$\omega^2 = f(\mathbf{g}(\theta) - \tilde{\mathbf{g}}(\theta)). \quad \dots\dots\dots \quad (13)$$

The minimum ω is achieved when $\mathbf{g}(\theta) = \tilde{\mathbf{g}}(\theta)$. ■

3.1. The Algorithm

The algorithm for the dynamics identification through natural oscillation of each link of a given manipulator is presented in the following.

1. Select large values for the inertia, mass, and center of mass to initialize the dynamics parameters of the manipulator links.
2. For each of the joint i, send the torque τ_i corresponding to the Coriolis and centrifugal forces and the gravitational term.
3. Give the system an initial perturbation to move it from rest. The system will now oscillate as an inverted pendulum.
4. Measure the frequency oscillation ω.
5. Adjust the values of the dynamics parameters to minimize the frequency of oscillation.
6. Repeat the previous step until the dynamics parameters corresponding to the minimum frequency of oscillation is found.

The dynamics parameters are initialized at large values to prepare the system for the experimental procedure. This is to avoid the system from falling due to insufficient torque sent at the joints. Because of the initially large joint torque τ_i, the manipulator will be vertically upright and is at rest when no outside forces are acting on it, except gravity. Then an outside force, normally at tip of the inverted pendulum, is applied to perturb it from rest and will cause the manipulator links to start to oscillate.

To measure the frequency of oscillation ω, normally the number of periods of oscillation is counted within a predefined number of computational cycles. An incremental step is performed within the search space of the dynamic parameters to find the combination of values that correspond to the minimum ω. The dimension of the search space increases as the number of dynamics parameters to be identified increases. Incrementally changing the values of the dynamic parameters and measuring the corresponding frequency of oscillation are repeatedly performed until the minimum ω is found. For higher degrees of freedom, it is highly possible that the identified parameters will result in a combination of possible range of values. Each of the possible combinations can be checked later against the robot response in the actual manipulator control. Admittedly, the limitation of this experimental method is due to the fact that the links, whose parameters are to be identified, have to be dependent on gravitational force. Other links that are not under the influence of gravitational force will be addressed in future work.

4. Results and Analysis

Simulations are performed to test the proposed algorithm in identifying the dynamics parameters of one and two degrees of freedom manipulators. Open dynamics engine (ODE), an OpenGL program integrated with C code, is used as the simulation platform. This simulation platform will need the actual physical model for the system to move in a virtual world. The dynamics parameters are then provided to create a model for the simulation. Then the corresponding torques are sent to the joints using estimated dynamics parameter values. In this section, the range of estimated values corresponding to the minimum frequency of oscillation will be presented for one, two, and three degrees of freedom simulated manipulator.

4.1. Accuracy of the Dynamics Model

The simplest case of one degree of freedom was used to test the sensitivity of the proposed experimental method to numerical errors. A mass factor f_m is multiplied to the gravitational term for the inverted pendulum such that the torque sent to the system becomes

$$\tau = f_m \frac{1}{2} mgl \sin\theta. \quad \ldots\ldots\ldots\ldots \quad (14)$$

Then a initial push is given to start the system to achieve natural oscillation. A fixed number of 5,000 computational steps was taken for every value of mass factor f_m and the number of periods are recorded. The results are shown in **Table 1**.

Table 1. Sensitivity of identification values to numerical errors.

Mass Factor f_m	No. of Periods per 5000 Updates
1.10	16
1.05	11
1.04	10
1.03	9
1.02	8
1.01	6
1.00	4
0.99	(falls under gravity)

The table shows that 0.01 difference from the actual mass and center of mass will already create a difference in the frequency of oscillation. The minimum frequency of oscillation is shown to be 4 periods out of the 5,000 computational steps. A mass factor $f_m = 0.99$ will already cause the system to fall due to gravitational force, because the values of mass and center of mass in the dynamics model, as stated in Eq. (14), were under compensated.

It is noted that when the product of mass m and length l results in a multiple of 1.0 to the actual physical model, the resulting frequency of oscillation is at the minimum. In a sense it is the lumped model of mass and center of mass that is identified such that any values of m and l would suffice to model the dynamics parameters as long as the product of their values corresponding to the actual physical model is correct to within 0.01 accuracy. This precision defines the range of possible values of mass m and length l.

4.2. Two Degrees of Freedom

The case of two degrees of freedom is shown. The symbolic form of the Coriolis and centrifugal forces c_i and gravitational terms g_i, where $i = 1, \ldots, n$ are shown below

$$\begin{aligned} c_1 &= -f_{m1}\, \tfrac{1}{2} m_2 S_2 l^2 \dot{\theta}_2^2 - f_{m1}\, m_2 S_2 l^2 \dot{\theta}_1 \dot{\theta}_2 \\ c_2 &= f_{m1}\, \tfrac{1}{2} m_2 S_2 l^2 \dot{\theta}_1^2 \\ g_1 &= f_{m2}\, (\tfrac{1}{2} m_1 + m_2) g l S_1 + f_{m3}\, \tfrac{1}{2} m_2 g l S_{12} \\ g_2 &= f_{m3}\, \tfrac{1}{2} m_2 g l S_{12} \end{aligned} \quad (15)$$

such that $S_{i\ldots n} = \sin(\sum_i^n \theta_i)$ and $C_{i\ldots n} = \cos(\sum_i^n \theta_i)$ and n denotes the number of degrees of freedom. Links one and two have equal link length l, and m_1 and m_2 are their respective masses. For each of the lumped inertia parameters, mass factors f_{m1}, f_{m2}, and f_{m3} are used. That is f_{m1} for $m_2 l^2$, f_{m2} for $(m_1/2 + m_2) l$, and f_{m3} for $m_2 l$. Although the concept of lumped inertias identification was used in [16], in that work it was necessary to have a symbolic dynamics model of the manipulator to be identified before the experiment can proceed. In this work, the dynamics model can be identified individually without the symbolic model. The value of the lumped dynamics pa-

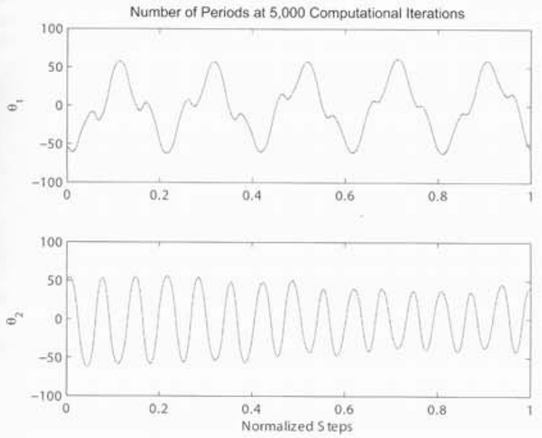

Fig. 3. The number of periods for each of the joints of the two degrees of freedom robot, recorded within 5,000 computational iterations. The x-axis showed the normalized computational iterations. This is the case of $f_{m1} = f_{m2} = f_{m3} = 1.01$ where the number of periods for link one is 5 and link two is 15.

Table 2. Two degrees of freedom response.

Mass Factor			No. of Periods per 5000 Steps	
f_{m1}	f_{m2}	f_{m3}	Link 1	Link 2
1.05	1.05	1.05	9	24
1.04	1.04	1.04	8	24
1.03	1.03	1.03	7	21
1.02	1.02	1.02	6	18
1.01	1.01	1.01	5	15
1.00	1.00	1.01	4	14
1.00	1.00	1.00	3	14
0.99	1.00	1.00	3	13
0.99	0.99	1.00	(falls under gravity)	
0.99	0.99	0.99	(falls under gravity)	

rameters model only served as the limit of the product of the identified dynamics parameters.

Figure 3 shows the joint displacement for each of the joints of the two degrees of freedom robot where $f_{m1} = f_{m2} = f_{m3} = 1.01$ as shown in **Table 2**. This table shows the experimental results for 5,000 computational steps of a two degrees of freedom robot with three mass factors f_{m1}, f_{m2}, and f_{m3}. The frequency of oscillation is recorded for the different values of the mass factors. The robot falls under the influence of gravity when at least two of the mass factors are 0.01 below the assigned physical mass factor of 1.0. The minimum frequency of oscillation applies when all mass factors are 1.0 and when one of the mass factors is 0.01 below 1.0. As shown in the table, when at least two of the mass factors are different by 0.01 from another set of values, a discrepancy in the frequency of oscillation is observed. This value will be used as a guide in future experimental results for higher degrees of freedom manipulator. The frequencies of oscillations for both links decreased accordingly with decreased values of the dynamics parameters. In this experiment, considering the frequency of oscillation of link one is sufficient to monitor the minimum value of the frequency of oscillation to identify the dynamic parameters. The link two frequency of oscillation can be used instead of link one in the dynamics parameters identification, but in this case, link two is only used to confirm the results derived from link one.

Table 3. Mass and center of mass identification for 3-DOFs.

Mass Factor $f_{m1}, f_{m2}, f_{m3}, f_{m4}, f_{m5}$	No. of Periods at 5,000 Updates Link 1, Link 2, Link 3
1.010	4.5
1.005	4.0
1.004	3.9
1.003	3.9
1.002	3.7
1.001	3.2
1.000	3.1
0.999	3.0
0.998	(falls under gravity)

4.3. Three Degrees of Freedom

The gravitational and Coriolis and centrifugal terms of a three degree of freedom is shown in Eq. (16). The link masses are m_1, m_2, and m_3 for links 1 to 3 and have equal link lengths of L.

$$\begin{aligned}
c_1 &= -f_{m5}\tfrac{1}{2}(m_2+2m_3)L^2\dot{q}_2(2\dot{q}_1+\dot{q}_2)S_2 \\
&\quad - f_{m4}\tfrac{1}{2}m_3L^2(\dot{q}_3(2\dot{q}_1+2\dot{q}_2+\dot{q}_3)S_3 \\
&\quad + (\dot{q}_2+\dot{q}_3)(2\dot{q}_1+\dot{q}_2+\dot{q}_3)S_{23}) \\
c_2 &= f_{m5}\tfrac{1}{2}(m_2+2m_3)L^2\dot{q}_1^2S_2 \\
&\quad + f_{m4}\tfrac{1}{2}m_3L^2(-\dot{q}_3(2\dot{q}_1+2\dot{q}_2+\dot{q}_3)S_3 \\
&\quad + \dot{q}_1^2S_{23}) \\
c_3 &= f_{m4}\tfrac{1}{2}m_3L^2((\dot{q}_1+\dot{q}_2)^2S_3+\dot{q}_1^2S_{23}) \qquad (16)\\
g_1 &= f_{m1}\tfrac{1}{2}(m_1+2(m_2+m_3))LgS_1 \\
&\quad + f_{m2}\tfrac{1}{2}(m_2+2m_3)LgS_{12} \\
&\quad + f_{m3}\tfrac{1}{2}m_3LgS_{123} \\
g_2 &= f_{m2}\tfrac{1}{2}(m_2+2m_3)LgS_{12} \\
&\quad + fm_3\tfrac{1}{2}m_3LgS_{123} \\
g_3 &= f_{m3}\tfrac{1}{2}m_3LgS_{123}
\end{aligned}$$

The values of f_{m1} to f_{m5} are varied to determine the system response at minimum ω. **Table 3** shows the experimental response of the three degrees of freedom manipulator. In the experiment, the natural oscillation is achieved at slow speed and the entire system moves in unison. This is helpful but not necessary, in achieving well-defined natural oscillations. The inertias were also expressed in terms of masses and centers of mass, and the dominant parameters are gravitational and not the Coriolis and centrifugal forces.

As in the previous results, there is a distinctive decrease of the period of oscillation as the mass factors f_{m1} to f_{m5} decrease towards the correct value. At mass factors of 0.998 the system fell under gravity. The minimum frequency of oscillation is achieved at a mass factor value of 0.999. The system can be considered as having a tolerance limit of ± 0.001. Such tolerance value is also demonstrated in mass factor values of 1.004 and 1.003 where the corresponding periods remain the same. For practical purposes, it can be stated that the tolerance value is at ± 0.002.

5. Conclusion and Future Work

This work showed a new method of identifying the dynamics parameters of multi-link rigid bodies that move under gravitational influence. A mathematical proof is presented to support the validity of the proposed algorithm. The idea is to compensate for the Coriolis and centrifugal forces and gravitational terms, and apply an outside force for the system to achieve natural oscillation. Once this is done, the experimental identification proceeds by minimizing the frequency of oscillation just before the system falls under the influence of gravity. The correct values of the dynamics parameters correspond to the system with the minimum frequency of oscillation. Results sensitivity and range of the identified experimental values were shown. The future direction of this work is to identify the dynamics parameters of higher degrees of freedom manipulators where the search spaces are much larger.

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