Experimental validation of a 2 degrees of freedom whisker sensor dynamic model

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Abstract: This paper describes a first stage of a research that aims to model a two degree of freedom artificial whisker based sensing system. The links model has been obtained. Additional elements and assumptions have been considered due to the real platform characteristics. An experimental platform has been designed to provide the whisker motion. Since this whisker has to be actively controlled, the obtained model should be useful for controlling the links tip. Furthermore, the whisker platform tries to simulate as much as possible the ability to rapidly reorient and target itself towards specific surfaces from different approachable angles. The link is made of a composite material, and therefore it involves non-linear expressions that govern the system dynamics. The whisker model is simulated by Simulink / Matlab and the experimental results that validate the model show the whisker model performance.

Keywords: Whisker, flexural dynamics, flexible arms, dynamic model.

1. INTRODUCTION

In nature, touch is an alerting stimulus which is also used to solve complex tasks such as: to determine object texture, position and shape; to distinguish soft from hard; to identify whether something is moving and its speed and direction (Prescott et al. (2009)). The controlled sweeping movements of the vibrissae are known as whisking. It is an important robotics challenge that aims at replicating some of vibrassal system functionalities in bio-mimetic robots.

Many mammals do large part of their tactile sensing at slight distance using long hairs as vibrissal sensors, in which bumps and troughs are translated to the vibrissal shaft and detected by pressure sensitive receptors inside of a specialized hair follicle. In this function the transducers or receptors are kept away from the contacted surface, which is a helpful option due to the problems that wear and tear of the repeated and direct physical contact might cause. Whiskers activity encodes information that allows to precisely localize contacted objects in a three dimensional space. It also helps some mammals to detect, recognize, track and catch their pray with speed and accuracy. In some species, especially those that are nocturnal or live underground the whiskers are more important than the eyes.

Research on artificial whiskers systems began in the middle 1980s and the recent progress has been encouraged by the increased understanding of natural vibrissal systems and the advances in engineering, microelectronics, transduction and actuation. The prospect of putting the tactile sensing capabilities onto artificial vibrissal systems in order to replicate some of the functionalities in robotics sensory systems, leads to demonstrate the potential of artificial vibrissal systems for a range of different task settings, including industrial relevant problems such as object sorting navigation in occluded environments and some other mobile robotic applications. New applications for tactile sensing including surgery, rehabilitation and service robotics have received significant levels of research attention e.g.: Lee et al. (1999); Giraldi et al. (2002); Boukhniffer et al. (2007); King et al (2006); Becedas et al. (2010).

A proper artificial whisker system design would differ from the passive binary collision detection that many contemporary robots are endowed. Some remarkable active whiskers applications have been carried out e.g.: Ueno et al. (1996); Clements et al (2006); Zhao et al. (2007); among others. To measure the 3D objects, by sliding the whisker across them, requires accurate regulation of the contact force, which has to be solved for a flexible system, as well as to control the vibrations at the end point.

There have been several works that incorporate different control designs and have improved the flexible link dynamic modeling, under the assumption of small elastic displacements (Benosman et al. (2004)). Some dynamic models have been proposed to analyze single links spring mass discrete model, lumped masses model, linear Euler-Bernoulli, generalized Newton and Euler algorithms, Lagrange equations, finite elements, etc. This paper makes used of a previous Euler-Bernoulli beam model which has been obtained in Castillo et al. (2010). It is a non-linear dynamic model and shows the most important flexural dynamics of the link. An important advantage of this model is that it remains useful for designing the tip position control, in order to precisely move and localize the whisker end-point. Simulations and experiments illustrate the good performance of the presented whisker model. The actual model accuracy in this work will allow us to design a high performance inversed dynamics control, which is going to be combined with an active vibration suppression control strategy.

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This paper is organized as follows. Section II states the whisker dynamic model of our system. The experimental platform description and setup are detailed in Section III. The model validation and results are presented in Section IV. The relevant conclusions are presented in Section V.

2. WHISKER DYNAMIC MODEL

2.1 Simplified dynamic whisker model

In a previous work (Castillo et al. (2010)) a simplified whisker dynamic model was described. The dynamics between the model inputs (motors control signal) and outputs (tip position) is of 8th order. In order to simplify the model, the system was splitted into two coupled 4th order models (see Fig.1 and Fig.2).

The motor dynamics is ruled by the following differential equations

\[\Gamma_\varphi = K_\varphi V_\varphi = J_\varphi \dot{\varphi}_m + \nu_\varphi \varphi_m + \Gamma_\varphi^{\text{coupl}} + \Gamma_\varphi^{\text{nlf}}\]

\[\Gamma_\theta = K_\theta V_\theta = J_\theta \dot{\theta}_m + \nu_\theta \theta_m + \Gamma_\theta^{\text{coupl}} + \Gamma_\theta^{\text{nlf}}\]

These equations are seen from the link side, \(\Gamma_\varphi\) and \(\Gamma_\theta\) are the motors torques, \(\Gamma_\varphi^{\text{coupl}}\) and \(\Gamma_\theta^{\text{coupl}}\) are the coupled torques, and \(\Gamma_\varphi^{\text{nlf}}\) and \(\Gamma_\theta^{\text{nlf}}\) are the non-linear components of the friction torques. The motors angles are \(\varphi_m\) and \(\theta_m\), and \(V_\varphi\) and \(V_\theta\) are the motor control signals. \(J_\varphi\) and \(J_\theta\) are the motors inertias, \(\nu_\varphi\) and \(\nu_\theta\) are the viscous friction coefficients of each motor, \(K_\varphi\) and \(K_\theta\) are the motors constants.

The potential elastic energy of the whisker is

\[E = \frac{1}{2}ml^2(\dot{\varphi}_m^2 + \dot{\theta}_m^2)\cos(\varphi)\]

\[+ \frac{1}{2}J_m \dot{\varphi}_m^2 + \frac{1}{2}J_\theta \dot{\theta}_m^2\]

The potential gravitational energy expression due to the whisker tip mass is

\[E_g = mgl \sin \varphi\]

The full system energy the dynamic model can be easily obtained. The system full energy can be written as

\[L = E_c + E_g + E_e\]

Here \(E_c\) is the gravitational energy, \(E_g\) and \(E_e\) is the elastic energy. The system kinetic energy is

\[E_c = \frac{1}{2}ml^2(\dot{\varphi}_m^2 + \dot{\theta}_m^2)\cos(\varphi)\]

\[+ \frac{1}{2}J_m \dot{\varphi}_m^2 + \frac{1}{2}J_\theta \dot{\theta}_m^2\]

The following system equations can be expressed in matrix form as

\[
\Gamma_i = \begin{pmatrix}
ml^2 \dot{\varphi}_m^2 \cos(\varphi) \\
2ml^2 \cos(\varphi) \sin(\varphi) \\
J_m \dot{\varphi}_m \\
J_\theta \dot{\theta}_m
\end{pmatrix}
- \begin{pmatrix}
-ml^2 \dot{\varphi}_m \cos(\varphi) \\
0 \\
0 \\
0
\end{pmatrix}
+ \begin{pmatrix}
mgl \sin(\varphi) \\
0 \\
0 \\
0
\end{pmatrix}
\]

\[
\frac{3EI}{l} \begin{pmatrix}
\sin(\varphi) \cos(\varphi) \cos(\theta_m - \theta) - \cos(\varphi) \sin(\varphi) \cos(\theta_m - \theta) \\
-\cos(\varphi) \cos(\theta_m - \theta) - \cos(\varphi) \sin(\varphi) \sin(\theta_m - \theta) \\
\cos(\varphi) \cos(\theta_m - \theta) - \cos(\varphi) \sin(\varphi) \cos(\theta_m - \theta) \\
\cos(\varphi) \sin(\varphi) \cos(\theta_m - \theta) - \cos(\varphi) \sin(\varphi) \cos(\theta_m - \theta)
\end{pmatrix}
\]

By taking the two first system equations from (8), and considering the trigonometric relationship between motor angles and tip angles.
\[ u_1 = \cos \phi_m \cos (\theta_m - \theta_t) \]
\[ u_2 = \cos \phi_m \sin (\theta_m - \theta_t) \]  
\( \tag{9} \)

the next non-linear expressions that govern the system dynamics can be obtained

\[ \dot{\phi}_t = -\left[ \dot{\theta}_t \sin \phi_t \cos \phi_t + K_s \cos \phi_t + K_a \left( \sin \phi_t u_1 - \cos \phi_t \sin \phi_m \right) \right] \]
\[ \dot{\theta}_t = 2 \tan \phi_t \dot{\theta}_t \phi_t + \frac{K_a}{\cos \phi_t} u_2 \]  
\( \tag{10} \tag{11} \)

where,

\[ K_a = \frac{3EI}{ml^3} \]
\[ K_g = \frac{g}{l}. \]  
\( \tag{12} \)

However, the designed experimental platform does not fit the particular simplified model when some more elements have to be added to the whisker platform, such as the whisker load transducer, which converts an input mechanical force and torque into an electrical output signal, as well as the transducer holder. Since the real platform has to be modified, the dynamic model will be adapted to the new requirements.

2.2 New whisker considerations and adjusted dynamic model

Due to the needs of placing a load sensor on the whisker system, this second model has to consider adding a rigid element, under the assumption that the transducer and its holder are rigid elements. Repeating the process of subsection 2.1, with the new mechanical configuration (see Fig.4 and Fig.5), yields a quite complex dynamic model which is difficult to be used for the controllers design. Then, we propose a simplified dynamic model, which is a straightforward extension of the model (8) to (12). Subsequently, we check experimentally its accuracy in order to validate it.

In this way, by assuming the new platform parameters and considering the experimental results that have been obtained, the actual dynamic model expressions (10) and (11) will remain as the system dynamic model expressions but the constants \( K_a \) and \( K_g \) of the new model are:

\[ K_a^* = \frac{3EI}{ml_2 (2l_2^2 + l_1^2)} \]
\[ K_g^* = \frac{g l_2}{(2l_2^2 + l_1^2)} \]  
\( \tag{13} \)

Fig. 4. Whisker Schematic: Complete Scheme with a Rigid \( l_1 \) and \( l_2 \) a Flexible link.

Fig. 5. The Experimental Platform.

Here, \( l_1 \) is the rigid arms length and \( l_2 \) is the flexible links length. The whisker vibration amplitude reduces with time because the full kinetic energy of the system decreases. Since the internal energy dissipation in the whisker is a fact, we must consider the mechanisms which absorb energy from the structure during its dynamic response which are responsible for the damping. Every parameter in (10) and (11) can be calculated by means of the whisker material and geometry parameters. However, the two new terms added to the model, \( \mu_1 \) and \( \mu_2 \), that consider the friction at the tip mass and the integral energy dissipation in the beam, must be adjusted experimentally. In our model these terms are part of a fitting process, which yields the best proportional coefficients. This method consists in identifying the damping coefficients by performing many experiments, measuring the damped tip response due to a simple link momentum (when the link is clamped). Then, the process fits equations of approximating curves to the field data in order to obtain a curve with a minimal deviation from all data. This best-fitting curve can be obtained by the method of least squares. The obtained values have been tested again when the link is driven by servo actuators to finally adjust the damping values. These procedure and its results are influenced by the motor position control performance due to the additional motor steady state error of each maneuver. In this way, two more terms have been added to the model \( \mu_1 \dot{\phi}_t \) and \( \mu_2 \dot{\theta}_t \) in order to consider the friction at the tip mass and the integral energy dissipation in the beam. The respective dissipation coefficients, \( \mu_1 \) and \( \mu_2 \), are shown in Table1. Subsequently, the following system dynamics expressions are

\[ \dot{\phi}_t = -\left[ \dot{\theta}_t \sin \phi_t \cos \phi_t + K_s^* \cos \phi_t \right. \]
\[ \left. + K_a^* \left( \sin \phi_t u_1 - \cos \phi_t \sin \phi_m \right) \right] + \mu_1 \dot{\phi}_t \]  
\[ \dot{\theta}_t = 2 \tan \phi_t \dot{\theta}_t \phi_t + \frac{K_a^*}{\cos \phi_t} u_2 + \mu_2 \dot{\theta}_t \]  
\( \tag{14} \tag{15} \)

3. THE EXPERIMENTAL PLATFORM

3.1 Whisker link

The flexible link is made of carbon fiber, the necessary whisker parameters and features are listed in Table 1.

3.2 Actuators

The experimental platform consists of a whisker that is attached to the output axis of two Harmonic Drive mini servo DC motor.
Table 1. Whisker Characteristics.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible link</td>
<td>R</td>
<td>0.001 m</td>
</tr>
<tr>
<td>Length l_2</td>
<td>0.5 m</td>
<td></td>
</tr>
<tr>
<td>Cross section</td>
<td>3.1416 x 10^{-6} m^2</td>
<td></td>
</tr>
<tr>
<td>Inertia moment</td>
<td>7.8540 x 10^{-11} m^4</td>
<td></td>
</tr>
<tr>
<td>Young module E</td>
<td>209 x 10^9 N/m^2</td>
<td></td>
</tr>
<tr>
<td>Density ρ</td>
<td>1780 kg/m^3</td>
<td></td>
</tr>
<tr>
<td>Natural frequency ω_n</td>
<td>6.54 x 10^{-1} s^{-1}</td>
<td></td>
</tr>
<tr>
<td>Tip mass load m</td>
<td>0.00578 kg</td>
<td></td>
</tr>
</tbody>
</table>

Rigid arm

| Length l_1    | 0.033 m |

Dissipation terms

| Coefficient μ_1 | -0.170 |
| Coefficient μ_2 | -0.050 |

PMA-5A set. Every set is composed of a servo motor, zero backlash reduction gear (relation n = 100) and an encoder.

3.3 Sensor system

The sensor system is integrated by the encoders, which measure the servo motor angles, and a 3D camera based measurement system OPTOTRACK. The encoders precision is 7 x 10^{-5} rad. The camera based system consists of three cameras that can provide the tip position by means of spherical markers which reflect infrared light. Every camera is calibrated previously, and the precision of the OPTOTRACK system is 0.3 mm.

4. MODEL VALIDATION

In order to validate the proposed dynamic model, several experiments have been performed. However, this work presents three experimental cases to be compared to the model based simulated results. They are case 1 in which the whisker movement is performed in the horizontal plane, case 2 the movement is performed in the vertical plane, and case 3 in which both movements are performed simultaneously. Some dynamic model parameter has been determined from specific experiments (e.g.: r, l_1, l_2 and m), and then validated by comparing experimental and simulated dynamic movements in the three aforementioned cases. The inertia moment I due to the links cross section is calculated by formula, the young modulus E was obtained by performing several experiments.

4.1 Motion controllers

The motion controllers that have been chosen are known as algebraic controllers and will ensure a good performance of our platform as it has been explained in (Castillo et al. (2010)). These controllers have to deal with disturbances such as non-modeled components of the friction, as well as provide precise and fast actuators positioning response at the link shaft. Some important aspects to take into account are the actuator identification and the non-modeled friction components identification, which are key matters for the controller design. Since the coupling torque is insignificant due to the reduction gear relation, there is no compensation of coupled torques.

The controllers design should never allow the motor saturation limit, and then the respective controller poles allocation has to consider it. 4th order trajectories have been designed as controller inputs (see Table 2), which will ensure smooth trajectories as well as fast motion performance. It has to consider the links physical constraints (Ramos et al. (2008)).

The objective of this paper is to validate the dynamic model obtained in the previous section 2. Note: In order to set the most realistic comparative scenario (simulations and experimental results), the obtained encoder signals from experiments are actually used in simulations as input for the simulated model. The motor real tracking performance is relevant for this case of study because in this study we are comparing the effectiveness of a dynamic model when it is compared to real platform performance.

4.2 The trajectory references

Table 2 shows the trajectories references that are given to the controllers as inputs. The full experimental time registered was 15 seconds for each experiment. Every whisker maneuver has been designed to do not produce large link deflection.

Table 2. Reference Trajectories.

<table>
<thead>
<tr>
<th>Case</th>
<th>( \theta_m )</th>
<th>0 - 1.0472 (rad.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi_m )</td>
<td>0 - 0.7854 (rad.)</td>
<td></td>
</tr>
<tr>
<td>( \theta_m ) and ( \phi_m )</td>
<td>0 - 0.7854 (rad.) both trajectories</td>
<td></td>
</tr>
</tbody>
</table>

4.3 Results

Fig.6 and Fig.7 illustrate the 4th order trajectory measured by the encoders at the output shaft, as well as the tip experimental and simulated response. In each case spherical coordinates have been used to present the trajectory data, as it is shown in Table 2. From the figures we can see that the simulated model accurately replicates the vibration frequency at the whisker tip. However, there are some amplitude differences which are going to be illustrated by obtaining the absolute error for each case.

The following figures show the absolute whisker tip position

Fig. 6. Experimental and simulated tip position - case 1 error between the simulated model and the experiments, when the whisker is driven by the servo motors. The dynamic model has provided a simulated data that effectively replicate the flexural behavior of the whisker. The absolute error results that have been obtained for each case are shown below (see Fig. 8, 9 and 10). The absolute error is under 5% for each experiment in almost the whole experimental time. Fig.8 shows that the absolute error in the inclination angle has an offset. This offset is cause by the static beam deflection due to the gravity. Evidently, this inclination offset angle can be observed in the
5. CONCLUSIONS

A simplified dynamic model has been proposed for two degrees of freedom very flexible whisker, including the kinematics and inertia effects of the load sensor placed at the base of the link.

The proposed nonlinear expressions present a very simple form, which is helpful for developing an external control loop that can easily cancel the nonlinear terms of the dynamic model expressions, e.g. by state feedback linearization. This model has been validated experimentally and it captures adequately the significant dynamics of the whisker. The model accuracy with respect to the real system probes that is an effective tool to implement the inverse dynamics based control strategy. In addition, the control strategy can be combined with an active technique for suppressing the whisker vibration. Further work includes the analytical justification of the experimentally obtained model, by deriving its equations from mechanics laws, and the design of a multi variable controller that can move the whisker tip faster and accurately. On the other hand, by using a load cell sensor in future works we can enhance the full active control and combine this inversion with further active techniques that aim to finally compensate the tip vibration.

REFERENCES


