Proceedings of the 9th WSEAS International CSCC Multiconference: CIRCUITS '05, SYSTEMS '05 COMPUTERS '05, COMMUNICATIONS '05

Vouliagmeni, Athens, Greece, July 11-16, 2005

HONORARY EDITORS:

Panos Pardalos (USA)
Irwin W. Sandberg (USA)
Stamatios Kartalopoulos (USA)

EDITORS:

Nikos E. Mastorakis (Greece)
Kostas Passadis (Greece)

ASSOCIATE EDITORS:

Argyrios Varonides (USA)
Francoise Preteux (France)
Christos Makris (Greece)
Minh Hung Le (Australia)
Vasilis Aggelis (Greece)
Edmary Altamiranda (Colombia)
Jose L. Villaveces (Colombia)
Guillermo Restrepo (Colombia)
Vincenzo Niola (Italy)
Mitica Craus (Romania)
Athanasios Drigas (Greece)

WSEAS

http://www.wseas.org

ISBN: 960-8457-29-7

Experimental Apparatus for Vibration Analysis in Robotics

MIGUEL F. M. LIMA
Electrical Engineering Department
Superior School of Technology of the Polytechnic Institute of Viseu
Campus Politécnico de Repeses, 3504-510 Viseu
PORTUGAL
lima@elect.estv.ipv.pt

J.A. TENREIRO MACHADO
Dept. of Electrical Engineering
Institute of Engineering of the Polytechnic Institute of Porto
Rua de S. Tomé, 4200-072 Porto
PORTUGAL
jtm@dee.isep.ipp.pt

MANUEL CRISÓSTOMO
Institute of Systems and Robotics
University of Coimbra
Polo II, 3030-290 Coimbra
PORTUGAL
mcris@isr.uc.pt

Abstract – Robotic systems use different types of sensors both in control and in environment perception. Those sensors can be digital encoders, tachometers, accelerometers, force sensors, current sensors and many others. In this paper an experimental setup is presented to study vibrations and impacts. The system acquires data from the sensors, in real time, and, in a second phase, processes it through an analysis package. Several examples with experimental results are carried out showing the functionalities of the developed apparatus.

Key-Words: - Vibrations, Impacts, Acquisition System, Robotics, Sensors, Real Time

1 Introduction

The advent of lightweight arm manipulators, mainly in the aerospace industry where weight is an important issue, leads to the problem of intense vibrations.

On the other hand, robots interacting with the environment often generate impacts that propagate through the mechanical structure and produce also vibrations.

This article describes an acquisition system developed to analyze these phenomena. The manipulator motion produces vibrations, either from the structural modes or from end-effector impacts. The instrumentation system acquires signals from multiple sensors that capture the axis positions, mass accelerations, forces and momentums and electrical currents in the motors.

Bearing these ideas in mind, this paper is organized as follows. Section 2 addresses the motivation for this work. Sections 3 and 4 describe the robotic system enhanced with the instrumentation setup and experimental result, respectively. Finally, section 5 draws the main conclusions and points out future work.

2 Motivation

Singer and Seering [1] mention several techniques for reducing vibrations and its implementation either at the robot manufacturing stage or at the operational stage. Briefly, the techniques can be enumerate as: (i) conventional compensation, (ii) structural damping or passive vibration absorption, (iii) control based on the direct measurement of the absolute position of the gripper, (iv) control schemes using the direct measurement of the modal response, (v) control driving, actively, energy out of the vibration modes, (vi) use a micromanipulator at the endpoint of the larger manipulator and (vii) adjustment of the manipulator command inputs so that vibrations are eliminated.

The work presented here is a first step towards the implementation of the sixth technique.

In recent years the use of micro/macro robotic manipulators has been proposed for space applications and nuclear waste cleanup. Several authors have studied this technique, namely Magee, *et al.* [2] and Cannon, *et al.* [3] that adopted the command filtering approach in order to position the micromanipulator. Also, Cannon, *et al.* [3] and Lew, *et al.* [4] used inertial damping techniques taking advantage of a micro manipulator located at the end of a flexible link.

The experiments described in this paper use a macro manipulator, with a low bandwidth, that is compensated through a much faster micromanipulator inserted at the robot endpoint.

3 The Experimental Setup

The developed experimental setup has two main parts: the hardware and the software components. In the following sub-sections these components are described.

3.1 The Hardware Components

The hardware architecture is shown in Fig. 1. Essentially it is made up of a manipulator robot, a Personal Computer (PC) and an interface electronic system. The interface box is inserted between the robot arm and the robot controller, in order to acquire the internal robot signals; nevertheless, the interface captures also external signals, such as those arising from accelerometers and force/torque sensors, and controls the external micro-arm. The modules are made up of electronic cards specifically designed for this work. The function of the modules is to adapt the signals and isolate galvanically the robot's electronic equipment from the rest of the hardware required by the experiments.

The force/torque sensor is the 67M25A model (JR3 Inc), comprising the sensor and a Digital Signal Processing PCI card, and is mounted on the robot's wrist. Two aluminum pancakes were built to mechanically adapt the sensor to the flexible beam, on one side, and to the robot arm, on the other side. The digital signals from the sensor run through a cable along the length of the arm, and go into a JR3 PCI receiver card inside the PC which processes the data at 8 kHz per axis. The card has built in filtering, but raw force signals were adopted in the following experiments.

Two general purpose analog 1-axis piezoelectric accelerometers are used. Both are the same type, Model FA 208-15 with a range of ±5 g from FGP Instrumentation. The body of the accelerometer sensors is mounted electrically isolated from the manipulator robot in order to prevent ground loops of electrical currents. Actually, without the accelerometers' isolation the signal presents a high level of noise that corrupts the main signal. One accelerometer is attached at the free-end of the flexible beam to measure its oscillations. The second accelerometer is attached on the clamped end of the flexible beam. Both accelerometer signals are processed through an A/D converter.

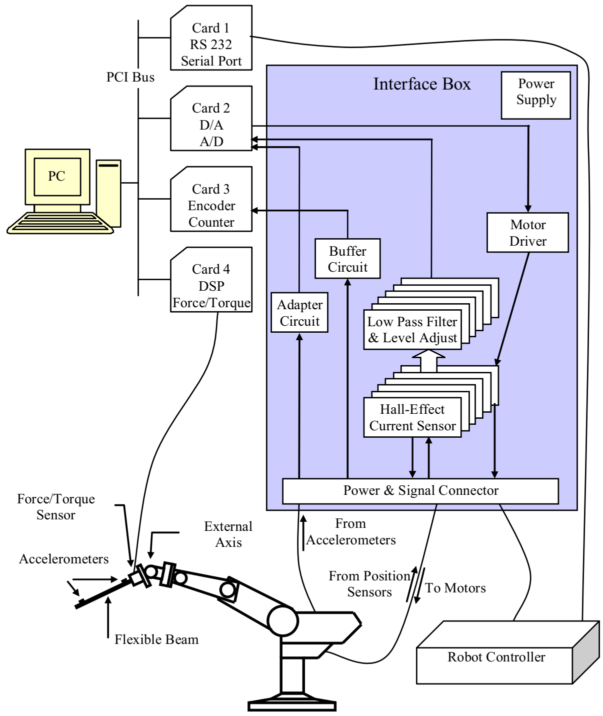


Fig. 1 – Block diagram of hardware architecture.

The robot used is an anthropomorphic type with five degrees of freedom (dof), model Scorbot ERVII from Eshed Robotec. To measure the electrical current supplied to each motor a Hall-effect sensor is inserted to avoid interfere with robot electronics. A circuit board was developed to handle the signal from the sensor up to the A/D converter. The power supplied to the motors is based on a pulse width modulation (PWM) driver with a frequency of 20 kHz. The motors rotate according with the DC component of electrical current and, in order to measure it, a low-pass filter was implemented for each measurement channel. Thus, a first function of the interface circuit is to filter the high frequency components of the signal and a second function is to galvanically isolate the electrical circuit from the robot electronics.

The power of the external axis servomotor is supplied by a dc linear amplifier driver model ELD-3503, from Portescap, that receives the voltage reference generated by the Card 2 D/A converter (Fig. 1).

The robot system and the external axis servomotor have position sensing by means of optical incremental encoders. Those position signals are also captured by the data acquisition system presented here. In order to isolate the robot feedback circuit from the PC card, for each encoder it is inserted a buffer (in the interface box) before connecting the signals to the corresponding high speed counter (in Card 3). This PC card is a high-speed counter/timer, PCI-6602 model from National Instruments and was programmed to read the signals from the encoders.

The A/D and D/A converters have a resolution of 12 bits and are implemented by a PCI-6024 model from National Instruments. This card is a multifunction I/O device and has sixteen analog inputs and two analog outputs. In this experiment we use eight analog inputs and one analog output. This card has also a general purpose counter and timer that was programmed to generate hardware interrupts to trigger the Interrupt Service Routine (ISR) described in section 3.2.

The transmitting and receiving of data between the computer and robot is carried out through a serial port RS 232C.

3.2 The Software Components

The Software runs in a Pentium 4, 3.0GHz PC. In fact, performing the data acquisition task from PC is very attractive because of their high-speed processing, low cost and great popularity.

The software architecture is shown in Fig. 2. The software package developed, from the user's point of view, consists of two applications. One, the acquisition application, is a program made up of two parts: The Graphical User Interface (GUI) module and the real time module. The other application is an Analysis Package program that analyses the data obtained and recorded by the acquisition application.

3.2.1 Real Time Software

The real time software developed for this application is based on the commercial solution Hyperkernel [7]. Hyperkernel is not a process executed on Windows NT/2000. It is a complete operating system running on a separate, parallel memory space which provides an extremely deterministic response to external events, interrupts and timers. It has its own set of services such as file access, shared memory with windows, interprocess communications, serial port, ethernet communications, and several other features. The Hyperkernel allows direct access to hardware, whereas Windows does not. Nevertheless, presently Hyperkernel allows only compatibility with Windows NT/2000.

These characteristics allow the development of tasks in the Hyperkernel environment to acquire data from various sensors, control the external axis and to have an online communication with the robot. Therefore, the system's functionality is split into many cooperating tasks.

The major disadvantage of Hyperkernel comes from the fact that it does not work with the drivers commonly offered by the manufacturers of the electronic cards. Therefore, it was necessary the time-consuming task of the development of all drivers for Cards 2, 3 and 4, with the manufacturer's support at register level programming.

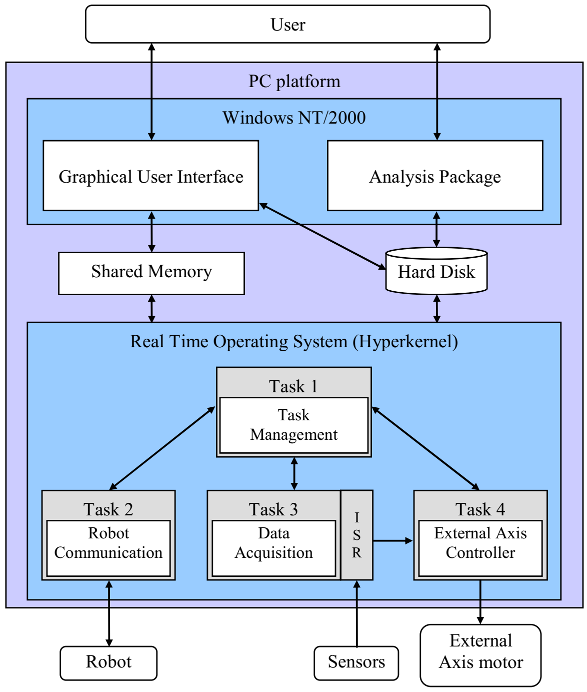


Fig. 2 – Block diagram of software architecture.

As shown in Fig. 2, were developed four tasks in the real time OS. The tasks work on a master slave philosophy: Task 1 is the master and Tasks 2, 3 and 4 are slaves that execute the orders.

Task 1 is the task manager and is responsible for controlling the execution of the other tasks. In a first phase, Task 1 starts the execution of the other tasks. In a second phase Task 1 receives orders from the user, via the GUI running in Windows, and prompts the slave tasks for its execution. In a final phase Task 1 kills the slave tasks.

Task 2 handles the communication with the robot controller via a RS232 link according to a protocol that implements a set of commands. A customized program was developed in the robot controller for this purpose.

Task 3 is the data acquisition task and is responsible for data gathering according with the requirements defined by the user, namely the sampling frequency, the duration time of the acquisition and which signals must be captured. In order to have hard real time performance an ISR was implemented. In the Hyperkernel environment, the ISR accesses the hardware directly, avoiding the heavyweight and unpredictable Windows NT interrupt handling. The data is time stamped and recorded on the hard disk and can be analyzed afterwards by other software tools. Therefore, Task 3 acquires data from Cards 2, 3 and 4. The data acquired concerning external axis control is available for Task 4.

Task 4 is the external axis controller and implements the control algorithm of the robot's external axis. The algorithm can be parameterized by the user or even replaced in order to test different control approaches. This task puts the result in the D/A converter of Card 2.

The real time software, running in the Hyperkernel, was developed in C based on a standard Windows NT/2000 development tool (MS Visual Studio) and the robot controller software was implemented in the ACL proprietary language.

3.2.2 Windows NT/2000 Software

The Windows NT/2000 Software is made up of the GUI module of the acquisition system and Analysis Package.

As shown in Fig. 2, Windows NT/2000 provides the GUI to the acquisition system user. From this GUI the user runs the real time software described in the previous section. The layout of the GUI is shown in Fig. 3. The user can choose the features implemented by Task 3 and can parameterize several functionalities such as the external axis controller. An event window informs the operator about all the important events that occur during the acquired session.

The acquisition system software was developed in C++ with MS Visual Studio.

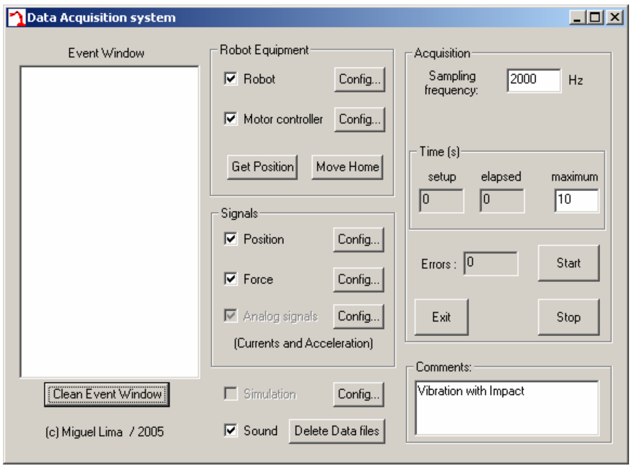


Fig. 3 – Graphical User Interface.

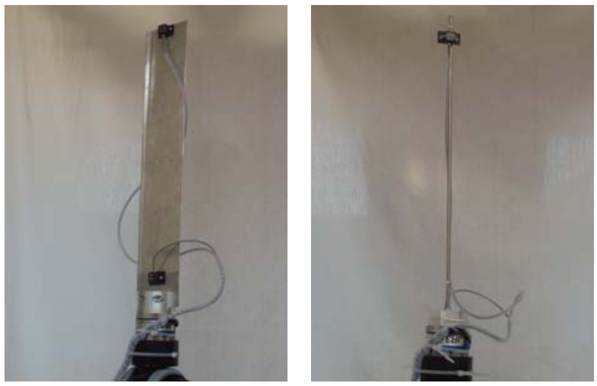
The Analysis Package, running off-line, reads the data recorded by the acquisition system and examines it. The Analysis Package allows several signal processing algorithms such as, Fourier transform, correlation, time synchronization, etc. With this software platform both the Hyperkernel and the Analysis Package tasks can be executed on the same PC.

4 Experimental Results

In this section two examples illustrate the functionalities of the experimental setup.

In the experiments are used two types of flexible links (Fig. 4). To show clearly the vibration phenomena, one link consists of a long, thin, rectangular, flexible aluminum beam clamped to the end-effector of the manipulator. The beam is rotated, using one joint of the manipulator, from an initial to a final position. During this motion, vibrations of the beam are excited due to inertial and Coriolis/centripetal forces. To test impacts, the other link consists of a long, thin, round, flexible steel rod clamped to the end-effector of the manipulator. The robot motion is programmed in a way that the rod moves against a flexible surface. Fig. 4 depicts the aluminum beam and steel rod.

The physical properties of the flexible beams are shown in Table 1. In this table, the accessories' weight characteristic represents the weight of the accelerometer,



(a) (b)

Fig. 4 – Flexible links: (a) Beam and (b) Rod.

Table 1 – Physical Properties of the Flexible Beams.

Characteristic	Aluminum Beam	Steel Rod
Density [kg m^{-3}]	2.71×10^3	7.86×10^3
Elasticity Modulus [N m^{-2}]	67.02×10^9	200×10^9
Weight [kg]	0.136	0.107
Length [m]	0.5	0.475
Thickness/diameter [m]	0.001	5.75×10^{-3}
Width [m]	0.1	- -
Accessories Weight [kg]	0.014	0.014

attached to the beam, and the auxiliary mechanical components needed for the experiment, which includes nuts, screws, electrical isolators, etc. This additional mass reveals to be important in the accuracy of the calculation of the beam vibration frequency. In fact, the accelerometers mass becomes important when measuring light test objects. Therefore, an additional mass can significantly alter the vibration levels and the frequencies at the measuring point. As a general rule [5], the accelerometer mass should be no more than one tenth of the dynamic mass of the vibrating part onto which it is mounted.

4.1 Vibration Example

Mechanical devices such as beams or rods, have distributed parameters such as mass, stiffness and damping, theoretically with an infinite number of dof, and are referred to as distributed-parameter systems. However, the analysis of these systems is eased by modeling them as discrete lumped-mass systems having a finite number of dof.

On the other hand, although damping is always present to some degree in all real systems, valuable insights can often be obtained by analyzing them as being theoretically undamped.

Along this line of thought, in this section we analyze the beam vibration considering a simplified lumped component model with one mass and one spring. A simple spring-mass system exhibits the natural frequency of [6]:

$$\omega_n = \sqrt{\frac{k}{m}} \quad [\text{rad s}^{-1}] \qquad (1)$$

where k [N m^{-1}] is the stiffness of the flexible element and m [kg] is the equivalent mass.

In the first experiment we adopt a cantilever beam system with a small damping. In a one dof lumped model, a single mass attached to the end of a spring element represents the effective mass of the beam.

The calculation of the equivalent mass and the spring constants of a cantilever beam can be expressed by the following equations (2) and (3).

The equivalent mass is given by:

$$m_{eq} = 0.24 m_{beam} \quad [\text{kg}] \qquad (2)$$

where m_{beam} [kg] is the mass of the beam.

The equivalent stiffness, or the equivalent spring constant is given by:

$$k_{eq} = \frac{3EI}{l^3} \quad [\text{N m}^{-1}] \qquad (3)$$

where E [N m^{-2}] is the elasticity (Young's) modulus, I [m^4] is the area moment of inertia of beam cross section, and l [m] is the length of the beam.

The formula for the area moment of inertia I for a rectangle cross section is:

$$I = \frac{b \cdot h^3}{12} \quad [\text{m}^4] \qquad (4)$$

where b [m] is the width and h [m] is the thickness.

Using the physical properties shown in Table 1 it yields a natural frequency of $f_n = \omega_n / 2\pi = 3.07$ Hz.

This value for f_n can be verified with the experiment under analysis. The clamped beam is rotated, using one joint of the manipulator robot, from an initial to a final position. During this motion, vibrations occur and the signal from the accelerometer attached at the free-end of the cantilever beam is recorded during 20 sec, with a sampling frequency of 500 Hz, as shown in Fig 5.

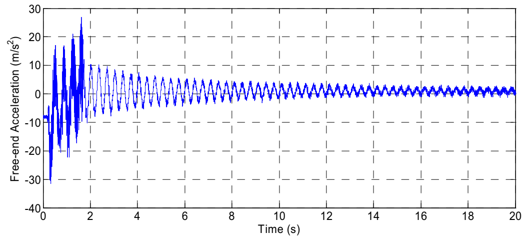


Fig. 5 – Signal of the accelerometer attached at the free-end of the cantilever beam.

The response consists on two components: (i) a fast transient approximately for $0 < t < 2$ sec and (ii) a slow transient response for $t > 2$ sec, also known as natural response, that depends only on the physical characteristics of the system itself.

Figure 6 shows the Fast Fourier Transform (FFT) of the signal that reveals, clearly, the natural frequency of the cantilever beam, as predicted by the analytical calculation.

Figure 7 depicts the electrical current of the motor axis used to rotate the beam.

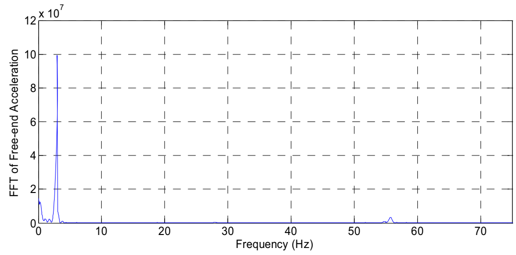


Fig. 6 – FFT of the free-end acceleration.

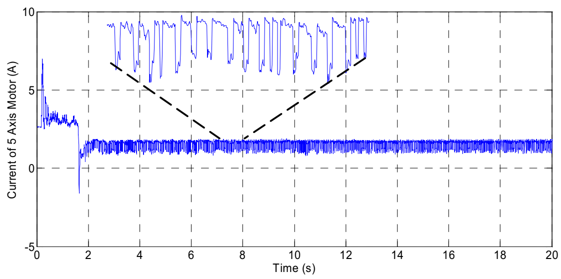


Fig. 7 – Electrical current of the axis motor

We conclude that approximately for $0 < t < 2$ sec it is required a large motor current that correlates with the fast transient of the link and the attached beam. A current zoom for $t > 2$ sec reveals the action of the robot control system ensuring the position control.

4.2 Impact Example

In this second example the clamped rod is moved by the robot against a flexible surface. During this motion, an impact occurs and several signals are recorded with a sampling frequency of 500Hz. The signals come from different sensors, such as accelerometers, force and torque sensor, position encoders and current sensors. Due to space limitations we are only depicting the more relevant signals.

Figures 8 and 9 show the force/moments at the end-effector and the electrical currents of the robot motors, respectively. The three signals correspond to: (i) the impact of the rod on a less flexible surface, (ii) without impact and (iii) the impact of the rod on a flexible surface.

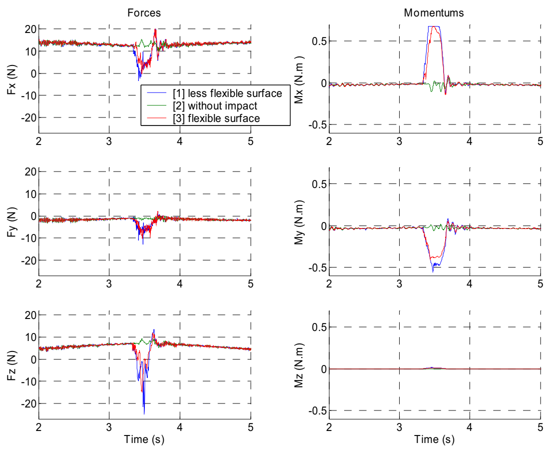


Fig. 8 –Forces and moments due to impact

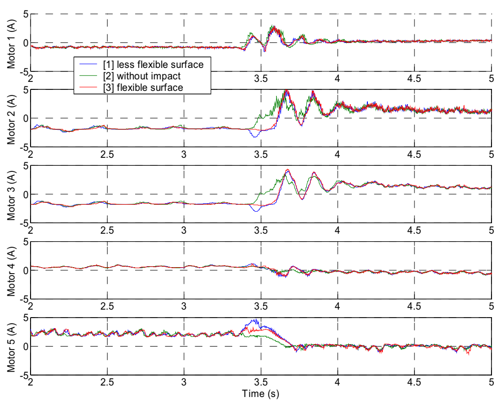


Fig. 9 – Electrical currents of robot axis motors

5 Conclusion and Future Work

In this paper an experimental set-up to study the vibrations and the impact phenomena in robotics was presented. During the vibrations or the impact phenomena several signals were recorded and evaluated.

The analysis package developed for this application allows the signal processing and shows its main characteristics. The examples have demonstrated the system capabilities and its effectiveness.

The next stage of development of the software and hardware apparatus is to reduce the vibrations and its effect upon the robot structure. In this line of thought, are under study the input shaping technique and the adoption of a micromanipulator, with a higher frequency response than the main manipulator, mounted at the end-effector and actively counter-acting the undesirable dynamics.

References:

[1] N. C. Singer and W. P. Seering, "Using Acausal Shaping Techniques to Reduce Robot Vibration", *Proc. IEEE Int. Conf. on Robotics and Automation*, Philadelphia PA., April 25-29, 1988.

[2] David P. Magee and Wayne J. Book, "Filtering Micro-Manipulator Wrist Commands to Prevent Flexible Base Motion", *Proc. American Control Conf.*, Seatle, Washington, June 1995.

[3] David W. Cannon, David P. Magee and Wayne J. Book, Jae Y. Lew, "Experimental Study on Micro/Macro Manipulator Vibration Control", *Proc. IEEE Int. Conf. on Robotics and Automation*, Minneapolis, Minnesota, April 1996.

[4] Lew, J.Y., Trudnowski, D. J., Evans, M. S., and Bennett, D. W., "Micro-Manipulator Motion Control to Suppress Macro-Manipulator Structural Vibrations", *Proc. IEEE Int. Conf. on Robotics and Automation*, Vol. 3, 1995, pp. 3116-3120.

[5] Brűel & Kjaer, "Measuring Vibrations", Available online:http://www.bksv.com

[6] John J. Craig, *Introduction to Robotics, Mechanics and Control*, Addison-Wesley, 1989

[7] Available online: http://www.nematron.com