Dynamic Registration for Dental Robotics

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***Abstract*—Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) technology is an important developing field in dentistry. These specialized CAD/CAM computer programs are used prior to surgery to determine implant placement and create customized dental prosthesis for various dental restoration procedures. The inaccuracies in the current non-automated methods for dental implants may lead to dental implant failure due to improper positioning of the implant. Our objective is to develop an autonomous robotic arm that completes the dental implant placement and crowning preparation procedures with higher accuracy than the current manual methods. The previous work from the Bionic's Lab "Dental Robotics" project executed implant placement procedures on static dental models fastened to a mounting plate using a robotic arm [Denso VM-B01G] with a dental tool attached. The current goal is to extend this application to work for moving dental models using dynamic registration. Dynamic Registration is a method to implement real-time indexing between two devices by using a passive robotic arm [Microscribe MX] as a feedback mechanism to maintain a desired registration. The robotic arm will execute the procedure while using the real time feedback from the passive arm to insure accurate implant placement. Our objective is to define and experimentally verify an algorithm to implement the dynamic registration for motion tracking between the tip of the dental drill and the site of the implant location. Further developments will account for integrating dynamic registration with the current operation procedure and then improving the accuracy of the procedure using post-operative scanning to verify the implant placement.**

I. Introduction

A. Motivation and Background

The inaccuracies in the current non-automated methods for dental implants may lead to dental implant failure due to improper positioning of the implant. The Bionics Lab "Dental Robotics" project's objective is to develop an autonomous robotic arm to complete the dental implant placement procedures with higher accuracy than the current manual methods. In our previous research, we were able to conduct dental implant placement procedures. The active robotic arm would move autonomously on a prepared surgical plan trajectory while holding the dental tool to mill the jaw and conduct the procedure. Our goal is to conduct these same procedures on non-fixed dynamic models that would mimic a human's motion during the operation. Although there are other methods for motion control, our goal is to use a mechanical system to sense the patient's movement using Dynamic Registration for high accuracy and quick response time. The passive robotic arm used in our procedures, Microscribe MX, is highly precise 3D digitizer with accuracy up to 0.002 inches (Immersion Corporation, 2006) . Additionally the straightforward direct kinematic equations do not require high computational power; once a control algorithm is developed and thoroughly tested, we plan to implement the procedure using embedded systems; this could increase the accuracy through real-time feedback and real-time response.

B. Previous Work

The project uses two six-degrees-of-freedom manipulating robotic arms: one that is active and another that is passive. The active arm has servo-motor actuators in each joint and can move itself, whereas the passive arm simply has optical encoders and can be moved by an outside force. The servomotors and optical encoders in these robotic arms give them the ability to detect the angle of each joint at any given period. These joint angles are used to find the location of the tip of the robotic arm, the "end effecter", using a process called "Direct Kinematics". This is a key component in our algorithm we developed to implement the "Dynamic Registration".

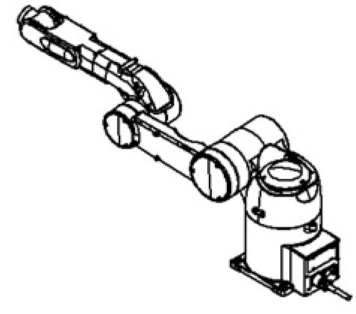
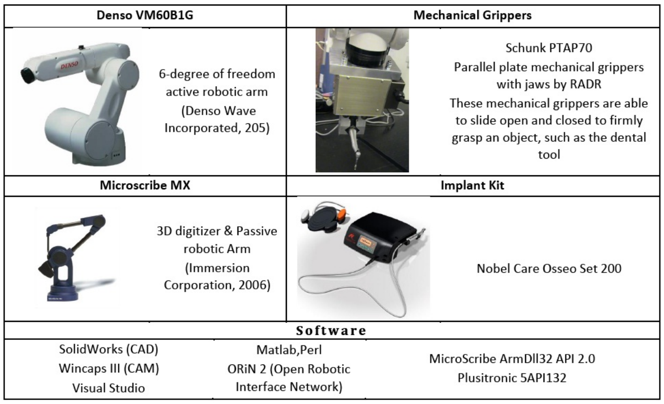


Fig. 1. SolidWorks generated model of the Denso Vm-B01G[2]

II. Procedure Implementation

A. Table of Equipment

This table shows the equipment used in the Dental Robotics experiment at the Bionics Lab:



Denso VM60B1G		Mechanical Grippers	
	6-degree of freedom active robotic arm (Denso Wave Incorporated, 205)		Schunk PTAP70 Parallel plate mechanical grippers with jaws by RADR These mechanical grippers are able to slide open and closed to firmly grasp an object, such as the dental tool
Microscribe MX		**Implant Kit**	
	3D digitizer & Passive robotic Arm (Immersion Corporation, 2006)		Nobel Care Osseo Set 200
Software			
SolidWorks (CAD) Wincaps III (CAM) Visual Studio	Matlab,Perl ORiN 2 (Open Robotic Interface Network)	MicroScribe ArmDll32 API 2.0 Plusitronic 5API132	

Fig. 2. Table of Equipment.

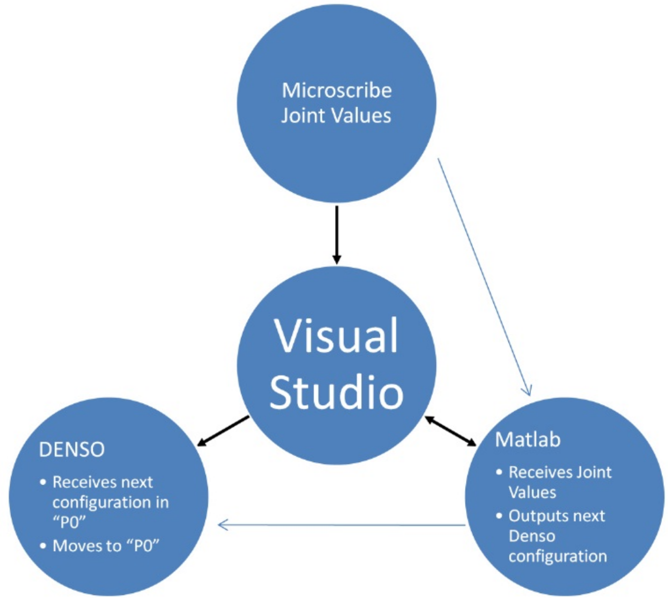


Fig. 3. Software implementation model

B. Procedure Methods

The dynamic registration procedure will work as follows:

- If a movement is detected by the passive robotic arm
- The robot stops the procedure
- An altered treatment plan based off the new location is computed (Matlab)
- The plan is uploaded directly to the robot's memory using network interfacing software (ORiN)
- The robot executes the treatment plan (altered) until complete or a movement is detected

III. Software Implementation

To conduct the proposed procedure, the active robotic arm is in an infinite loop program to move to a position variable 'P0'. This position variable is constantly being updated by the PC using a Visual Studio Program and ORIN's CAO dynamic link library. The Visual Studio program is polling data from the passive robotic arm every millisecond; once it has received data from the passive robotic arm, it computes the active robotic arm's corrected position and updates the Position variable 'P0'. The corrected position is computed in Matlab using direct kinematic techniques. This diagram shows how the visual studio program acts like a shell between the passive robotic arm, active robotic arm, and Matlab; the flow of the program is shown in the light blue lines, however the implementation is done through visual studio indicated by the bold black lines.

IV. Direct Kinematics for the Denso VM-B01G

The Denavit-Hartenberg Parameters for the Denso VM-B01G are shown in the figure below. There are 24 parameter values: four for each of the six different joints (including the joint angle). Additionally, there are six coordinate frames attached to each link denoted by the x and z axis that follow from the previous diagram of the DH values. There are many

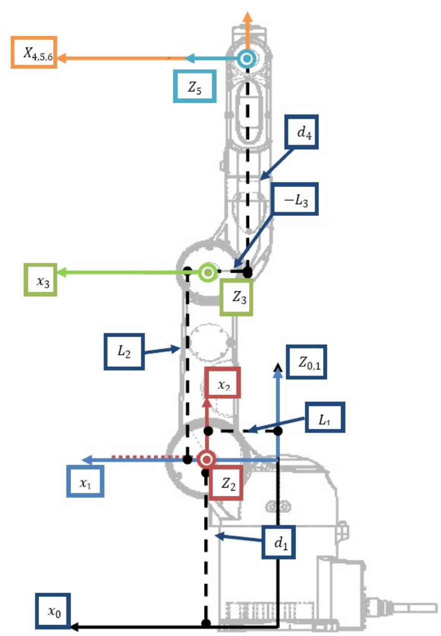


Fig. 4. SolidWorks generated model of the Denso Vm-B01G with DH parameters.[2]

approaches for finding the transformation matrix between each join of a manipulating robotic arm. The approach the Bionics Lab use is the "Modified Denavit-Hartenberg" approach that is outlined in Robert Craig's Introduction Rebotics book[1].

Each row of the DH table creates the following homogenous transformation matrices: ${}^{D_0}_{D_1}\mathbf{T}$, ${}^{D_1}_{D_2}\mathbf{T}$, ${}^{D_2}_{D_3}\mathbf{T}$, ${}^{D_3}_{D_4}\mathbf{T}$, ${}^{D_4}_{D_5}\mathbf{T}$,

TABLE I
DENAVIT-HARTENBERG PARAMETERS FOR THE DENSO VM-B01G

Link Number	Link Twist	Link Length	Link Offset
1	0	0	475mm
2	90	180mm	0
3	0	520mm	0
4	-90	-100mm	590
5	90	0	0
6	-90	0	0

and ${}^{D_5}_{D_6}\mathbf{T}$.
Then, the transformation from the base 0 frame to the end effector frame 6 is found by using the following equation:

$$ {}^{D_0}_{D_1}T * {}^{D_1}_{D_2}T * {}^{D_2}_{D_3}T * {}^{D_3}_{D_4}T * {}^{D_4}_{D_5}T * {}^{D_5}_{D_6}T = {}^{D_0}_{D_6}T \quad (1) $$

[1]
Similiarly, the transformation matrix ${}^{M_0}_{M_6}\mathbf{T}$ for the passive robotic arm, Microscribe MX, is found using this method using equation 1.

Using the process of Direct Kinematics, we are able to define the transformation from the base of the robotic arms to their end effectors based off joint angles. For the following discussion, we will define the transformation from the base to the end effector for the Denso, the active robotic arm, to be${}^{D_0}_{D_6}\mathbf{T}$ and the Microscribe MX, the passive robotic arm, to be ${}^{M_0}_{M_6}\mathbf{T}$.

V. DYNAMIC REGISTRATION ALGORITHM

The setup for a procedure with dynamic registration is shown in the following picture. The dental jaw is not attached to the mounting plate, instead it's attached to the passive robotic arm. Previously, the active robotic arm just held the dental tool with the dental jaw firmly attached to the mounting plate.

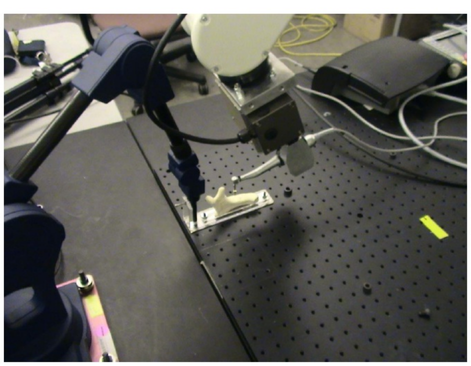


Fig. 5. Setup for the Dynamic Registration Procedure.

A. Step 1: Finding Static Homogenous Transformation Matrices

The first step is to define homogenous transformation matrices for the equipment used in the experiment that stay constant throughout the procedure. This refers to the transformation from the active robotic arm to the passive robotic arm and the ”tool transformations” for both robotic arms. One tool transformation is the transformation from the active robotic arm's end effector to the tip of the dental tool; the other is the passive robotic arm's end effector to the location of the implant site.

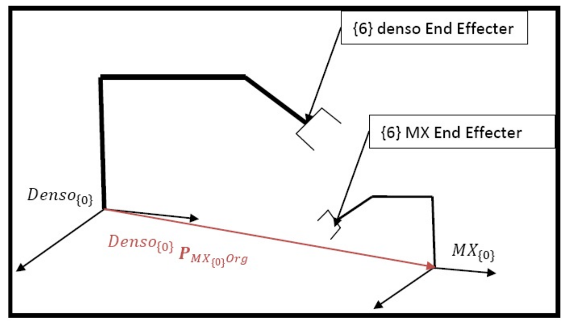


Fig. 6. Denso to Microscribe Transformation.

1) Denso to Microscribe Transformation: The Denso (Active robotic arm) and Microscribe Mx (passive robotic arm) are mounted on the table with their relative coordinate systems in the same orientation; hence, the homogenous transformation matrix describing the relationship consists of only translation.

1) From the base of the Denso to the base of the Microscribe, the distance to the is ${}^{\mathbf{D_0}}\mathbf{P}_{\mathbf{M_0}}$
2) Since there is no rotation between the two coordinate systems, the rotation matrix between base of the Denso to the base of the Microscribe, the identity matrix: ${}^{D_0}_{M_0}\mathbf{R} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$
3) Thus, the transformation matrix from the Microscribe End Effecter to the desired implant location with respect to the Microscribe end effecter is:

$$ {}^{D_0}_{M_0}\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & P_x \\ 0 & 1 & 0 & P_y \\ 0 & 0 & 1 & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2) $$

2) Passive Robotic Arm to Desired Implant Locaiton:

1) From the tip of the Microscribe, the distance to the desired implant location is: ${}^{\mathbf{M_6}}\mathbf{P}_{\mathbf{ImplantLoc}}$
2) Since there is no rotation between the two coordinate systems, the rotation matrix between the Microscribe's end effecter and the desired implant location with respect to the Microscribe's end effecter is the identity matrix: ${}^{M_6}_{implantLoc}\mathbf{R} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

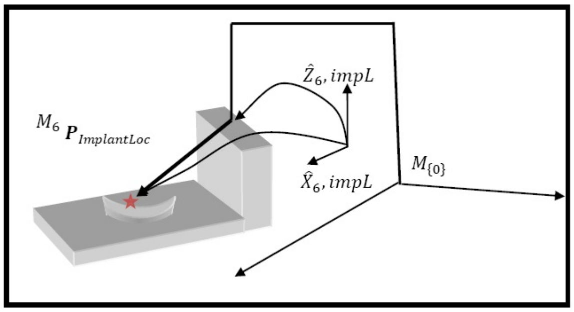


Fig. 7. Passive Robotic Arm to Desired Implant Location.

3) The transformation matrix from the Microscribe End Effecter to the desired implant location with respect to the Microscribe end effecter is:

$$ {}^{M_6}_{implantLoc}\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & P_x \\ 0 & 1 & 0 & P_y \\ 0 & 0 & 1 & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3} $$

B. Active Robotic Arm to the Dental Tool Tip

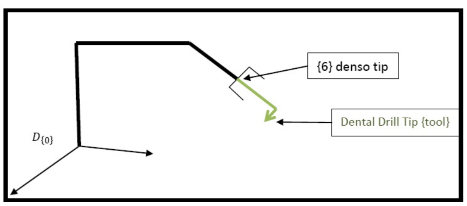


Fig. 8. Active Robotic Arm to the Dental Tool Tip

1) From the tip of the active robotic arm the distance to the dental tool tip is: ${}^{\mathbf{D_6}}\mathbf{P_{tool}}$
2) The rotation between the active robotic arm's end effector to the tool tip is: ${}^{D_6}_{tool}\mathbf{R}$
3) Then, the transformation from the active robotic arm's end effector to the tip of the tool is given:

$$ {}^{D_6}_{implantLoc}\mathbf{T} = \begin{bmatrix} {}^{D_6}P_{tool} & {}^{D_6}_{tool}R \end{bmatrix} \tag{4} $$

These matricess are calculated using the Denso's inteneral functions for tool callibration.

C. Step 2: Finding the Corrected Position Transformation Matrix

The key concept for dynamic registration is to obtain a constant confirgfuration between the tip of the dental tool and the dental implants.

By connecting the passive robotic arm to the dental implant model, we can manually move the dental implant to simulate a patients sudden undersired movement and know the new configuration of the tip of the dental implant. The movement is detected in the change of the non-static homogenous transformation matrix of the passive robotic arm ${}^{M_0}_{implantLoc}T => {}^{M_0}_{M_6}T^*$

where * indicates the new orientation.

It follows that the the active robotic arm needs to also move to retain the initial configuration: ${}^{D_0}_{D_6}T => {}^{D_0}_{D_6}T^*_{next}$

To find ${}^{D_0}_{D_6}T^*_{next}$ we can set up and solve the following set of equations:

Finding the desired implant location with respect to the base of the Denso:

$$ {}^{D_0}_{implantLoc}\mathbf{T} = {}^{D_0}_{M_0}\mathbf{T} * {}^{M_0}_{implantLoc}\mathbf{T} \tag{5} $$

$$ {}^{D_0}_{implantLoc}\mathbf{T} = {}^{D_0}_{tool}\mathbf{T} * {}^{tool}_{implantLoc}\mathbf{T} \tag{6} $$

Equating equation 11 and 12 for ${}^{D_0}_{implantLoc}\mathbf{T}$:

$$ {}^{D_0}_{M_0}T * {}^{M_0}_{implantLoc}T = {}^{D_0}_{tool}T * {}^{tool}_{implantLoc}T \tag{7} $$

Then, we can solve for

$$ {}^{D_0}_{tool}T = {}^{D_0}_{M_0}T * {}^{M_0}_{implantLoc}T({}^{tool}_{implantLoc}T)^{-1} \tag{8} $$

When jaw moves to new location it is changes the homogenous transfer matrix for the passive robotic arm: ${}^{M_0}_{implantLoc}T => {}^{M_0}_{implantLoc}T^*$

The position the active robotic arm needs to move to can be solved from Equation 13:

$$ {}^{D_0}_{tool}T_{next} = {}^{D_0}_{M_0}T * {}^{M_0}_{implantLoc}T^*({}^{tool}_{implantLoc}T)^{-1} \tag{9} $$

Once we have found the transformation for the active robotics' arm next position we can abstract the a position and fixed axis rotation.

$$ {}^{D_0}_{tool}\mathbf{T_{next}} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & P_{next_x} \\ r_{11} & r_{12} & r_{13} & P_{next_y} \\ r_{11} & r_{12} & r_{13} & P_{next_z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{10} $$

The next configuration of the robot's tool can be found by the translation: ${}^{\mathbf{D_0}}\mathbf{P_{tool_{next}}} = \begin{pmatrix} P_{next_x} \\ P_{next_y} \\ P_{next_z} \end{pmatrix}$

The orientation can be found using the X-Y-Z inverse matrix solution for fixed angles[1]

$$ R_{next_y} = Atan2(-r_{31}, \sqrt{r_{11}^2 + r_{21}^2} \tag{11} $$

$$ R_{next_z} = Atan2(\frac{r_{21}}{cos(R_{next_y}}, \frac{r_{11}}{cos(R_{next_y}}) \tag{12} $$

$$ R_{next_x} = Atan2(\frac{r_{32}}{cos(R_{next_y}}, \frac{r_{33}}{cos(R_{next_y}}) \tag{13} $$

These six values define the corrected Position variable for the active robotic arm:

$$NextPosition = \begin{pmatrix} P_{next_x} \\ P_{next_y} \\ P_{next_z} \\ R_{next_x} \\ R_{next_y} \\ R_{next_z} \end{pmatrix}$$

By constantly updating and moving the active robotic arm to the next position we can implement the dynamic registration algorithm.

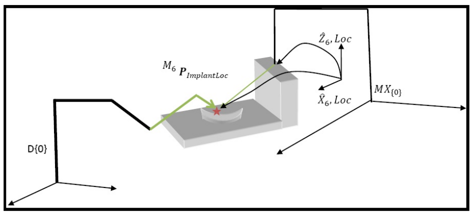


Fig. 9. Corrected Position Transformation

VI. Results

Using this workflow, we were able to successfully implement the motion tracking between the tip of the dental tool and the dental jaw model. The active robotic arm does in fact follow the passive robotic arm to achieve a constant orientation between both devices, however; the constant orientation has a static error of one to two millimeters. However, when both robotic arms are moving the error increases as well. Due to safety concerns, the active robotic arm's internal speed is set up to fifty percent of its maximum capacity. Additionally, the passive robotic arm outputs data at its minimum update period of two milliseconds and causes a significant delay in the motion tracking inhibiting real-time data streaming. The following graph shows data collected during a reference tracking experiment.

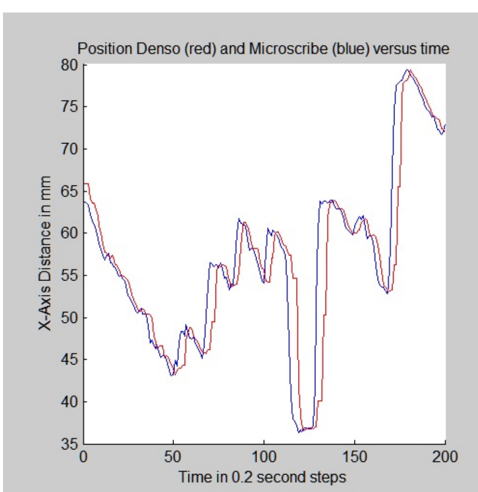


Fig. 10. Dynamic Registration X- Axis values

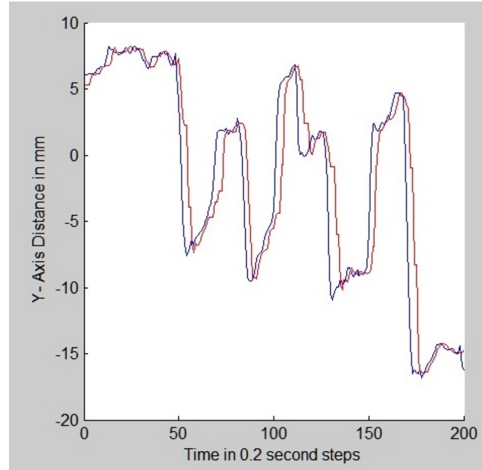


Fig. 11. Dynamic Registration Y- Axis values

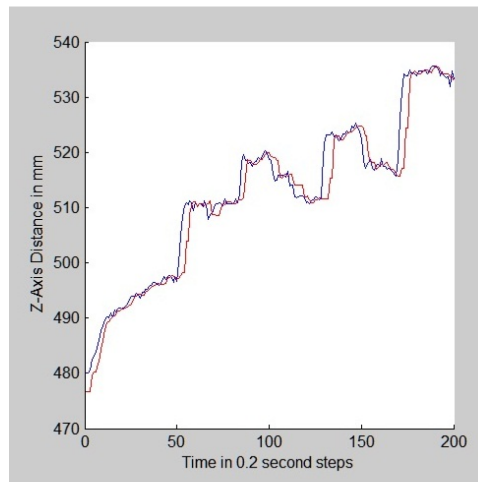


Fig. 12. Dynamic Registration Z- Axis values

In these diagrams the active robotic arm, shown in red, clearly trails the passive robotic arm, shown in blue. However, when the passive robotic arm is not changing positioin, the passive robotic arm "catches" up and decreases this offset.

VII. Conclusion

The inaccuracy in our current design is a limitation of our equipment. The error in the motion tracking of both devices is constant, indicating that there is an initial calibration error that could be solved using more precise grippers to hold the dental drill and the dental jaw. Additionally, the minimum update period of our feedback device is 2ms accounting for lag within the procedure.

Further developments will work on improving the accuracy of the current design along with intelligent trajectory planning. The dental tool follows the dental jaw; however, based on the orientation of the jaw, a sophisticated trajectory may be needed to safely move the dental tool to achieve its desired registration. After improving the accuracy of the current design, we plan to use postoperative scanning to verify and improve the quality of the procedures.

ACKNOWLEDGMENT

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[1] J. Craig, *Introduction to Robotics: Mechanics and Control*, 3rd ed. Upper Saddle River, NJ: Pearson, 2005.

[2] Denso Wave Incorporated, *Denso Robot Vertical Articulated VM-G Series: General Information about the Robot.* 2005.