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# ON THE KINEMATICS AND DYNAMICS OF DUAL–GRIPPER ROBOT MANIPULATOR

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**Abstract.** A dual-gripper Remote Tool Delivery (RTD) system has been developed to retrieve radioactive wastes from underground storage tanks with internal structural members. The RTD system is equipped with two grippers at both ends of the system. A vertical translation mechanism (VTM) is added which enables the vertical lifting motion of the system. The vertical movement can be processed with each gripper operating on a separate structural member. The dual-gripper design and inclusion of the VTM distinguish the RTD system from other ordinary robotic systems. These special features provide greater dexterity and flexibility; yet, increase the complexity in modeling and analysis. There are four possible operating configurations for the RTD system. The first configuration is that gripper 1 grasps the structural member in the tank while gripper 2 is free to move in space to perform designated task. In other occasions, it is possible that gripper 2 grasps the structural member and gripper 1 performs the necessary task. These two configurations typify the RTD system as an open-chain robotic system. It is also possible that both grippers grasp separate or the same structural members simultaneously. This exemplifies the RTD system as a closed-chain mechanism. The kinematics, dynamics and simulation of the open-chain robotic configurations are investigated in this paper.

**Key Words.** Dual-Gripper robot manipulator, Kinematic modeling, Kinematics, Dynamics, Simulation.

## 1. INTRODUCTION

The study of robot manipulation is concerned with the relationship between objects, and between the object and the manipulator. The key issues to be investigated include kinematics, dynamics and simulation of its operating conditions. A special dual-gripper robot manipulator –the RTD (romote tool delivery) system [1, 2]– is introduced and studied using the 4x4 homogeneous C-B (Cylindrical coordinates-Bryant angles) notation [5] in this paper. The shape (characteristic) matrix of each link is derived to describe individual link shape and joint characteristics geometrically. The direction (orientation) of each joint axis and position of each joint center in space then can be determined by a sequence of matrix multiplication. This geometric model provides basis for further kinematic, dynamic, and control simulation. Kinematics, dynamics and simulation of the RTD system [3, 4] are completed in Tele/IGRIP software package (Deneb Robotics, Inc.). The Tele/IGRIP simulation models can be useful for future real-time control applications.

### 1.1. The C-B Notation [5]

The 4x4 homogeneous matrix C-B notation is used to model the RTD system. The popular D-H notation describes only “relative” joint positions in space unless the adjacent joint axes are parallel or perpendicular to each other. However, the C-B notation will analyze the “exact” joint center positions in space; the D-H notation is considered the special case of the C-B notation.

The shape geometry of the spatial binary linkage, Fig. 1, can be described using the transformations of cylindrical coordinates and Bryant angles; thus termed "C-B notation." To transform the joint reference frame from $X_i$-$Y_i$-$Z_i$ to $X_{i+1}$-$Y_{i+1}$-$Z_{i+1}$; first, $X_i$-$Y_i$-$Z_i$ is transformed to $e_{xi}$-$e_{yi}$-$e_{zi}$ in the sequence ($\theta_i$, $h_i$, $r_i$) which corresponds to the cylindrical coordinate transformations; second, $e_{xi}$-$e_{yi}$-$e_{zi}$ is transformed to the resultant $X_{i+1}$-$Y_{i+1}$-$Z_{i+1}$ through Bryant angles ($\alpha_i$, $\beta_i$, $\gamma_i$); with $\gamma_i = 0^0$. The joint reference frame $X_i$-$Y_i$-$Z_i$

and principal joint parameters ( $\theta_i, h_i, r_i, \alpha_i, \beta_i$ ) for the *i*th joint $J_i$ are defined as follows.

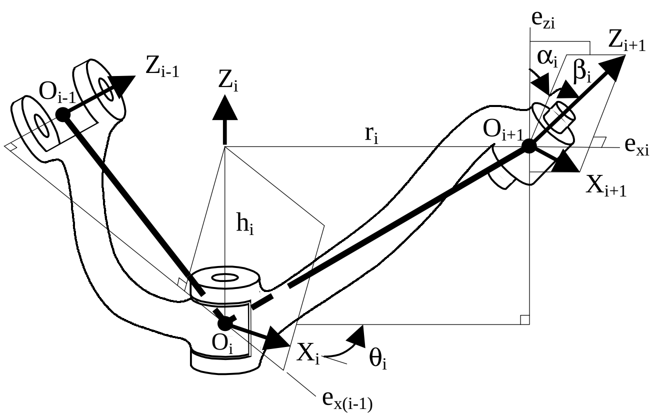


Fig. 1 The C-B notation

**<u>Joint Reference Frame</u>:** The origin $O_i$ of the *i*th joint local reference frame is chosen at the mechanical joint center, and

**$Z_i$** – along the *i*th joint axis in a designated direction.
**$X_i$** – prior to defining the $X_i$-axis, a reference line $e_{x(i-1)}$ must be specified that $e_{x(i-1)}$ passes through $O_i$ and intersects $Z_{i-1}$ perpendicularly in space. Then $X_i$ is defined as the axis normal to $Z_i$ in the plane $Z_i$–$e_{x(i-1)}$.
**$Y_i$** – in the direction to form a right-handed Cartesian coordinate system.

**<u>Principal Joint Parameter</u>:** Each successive transformation is based on the newly generated local coordinates.

**$\theta_i$** – rotating angle of the *i*th joint axis, measured about $Z_i$ from plane $Z_i$–$X_i$ to $Z_i$–$e_{xi}$.
**$h_i$** – the distance between joint centers $O_i$ and $O_{i+1}$ and measured along $Z_i$.
**$r_i$** – the distance between $Z_i$ and $O_{i+1}$ and measured normal to $Z_i$.
**$\alpha_i$** – twist angle, measured about $e_{xi}$ from plane $e_{xi}$–$e_{zi}$ to $e_{xi}$–$Z_{i+1}$. It is noticed that $X_{i+1}$ is on the plane $e_{xi}$–$Z_{i+1}$.
**$\beta_i$** – deviation angle, measured about $e_{yi}$ from $e_{zi}$ to $Z_{i+1}$.

The shape matrix $\mathbf{T}_i$ of the *i*th link formulated in C-B notation is, therefore,

$\mathbf{T}_i(\theta_i, h_i, r_i, \alpha_i, \beta_i)$ = (1)

$$\begin{bmatrix} c\theta_i c\beta_i - s\theta_i s\alpha_i s\beta_i & -s\theta_i c\alpha_i & c\theta_i s\beta_i + s\theta_i s\alpha_i c\beta_i & r_i c\theta_i \\ s\theta_i c\beta_i + c\theta_i s\alpha_i s\beta_i & c\theta_i c\alpha_i & s\theta_i s\beta_i - c\theta_i s\alpha_i c\beta_i & r_i s\theta_i \\ -c\alpha_i s\beta_i & s\alpha_i & c\alpha_i c\beta_i & h_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

in which the orientation and position of $X_{i+1}$–$Y_{i+1}$–$Z_{i+1}$, relative to $X_i$–$Y_i$–$Z_i$, can be abbreviated by the direction cosine matrix $\mathbf{D}_i$ and position vector $\mathbf{P}_i$ as

$$\mathbf{T}_i(\theta_i, h_i, r_i, \alpha_i, \beta_i) = \begin{bmatrix} & D_i & & P_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

## 2. KINEMATIC MODELING AND ANALYSIS OF THE RTD SYSTEM

The RTD (Remote Tool Delivery) system, Fig. 2, is equipped with a gripper at each end of the system to grasp the deployment mast or structural member in the tank [1, 2]. A vertical translation mechanism (VTM) is added to the system which enables vertical lifting motion of the system. These two special features provide greater dexterity and flexibility to the RTD system.

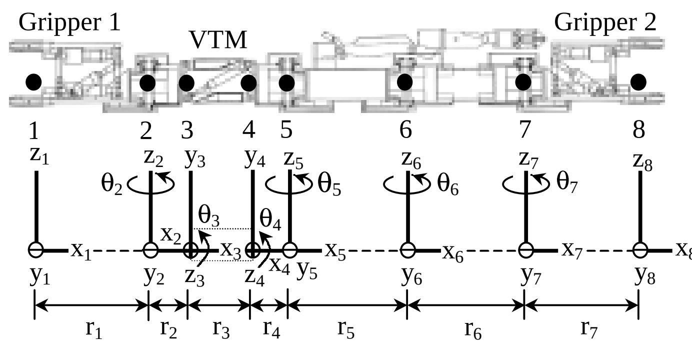


Fig. 2 The RTD system

As shown in the figure, local frame of reference for each joint is designated at its joint center and numbered. For instance, joints 1 and 8 indicate centers of gripper 1 and 2, respectively. The VTM, a 4-bar parallelogram mechanism, is located between joints 3 and 4 and adjacent to gripper 1. The middle section of the system is defined between joints 5 and 6 with link length $r_5$. This midsection can carry a slave arm as shown in the figure for local operations. Since the VTM elevates or descends the system vertically, the horizontal distance $r_3$ varies with vertical elevation or descent. However, other link lengths remain constant at all times.

Two operating modes are possible: 1) the vertical movement can be processed with each gripper grasping a separate structural member, or 2) the system can fold itself so that both grippers grasp the same structural member. The first operating mode typifies the open-chain robotic system that will be investigated in this paper. The second mode can be characterized as a closed-chain mechanism and will be studied in a separate paper. Two cases are considered for the open-chain RTD robotic system. They are 1) gripper 1 (relatively fixed and) grasps the structural member in the tank whereas gripper 2 is free to perform the assigned tasks, and 2) gripper 2 (relatively fixed and) grasps the structural member in the tank while gripper 1 is free to move in space.

### 2.1. Gripper 1 grasps the structural member in the tank

A concept for the first operating configuration of the RTD system is shown Fig. 3, where gripper 1 grasps the structural member in the tank and gripper 2 is free to move in space.

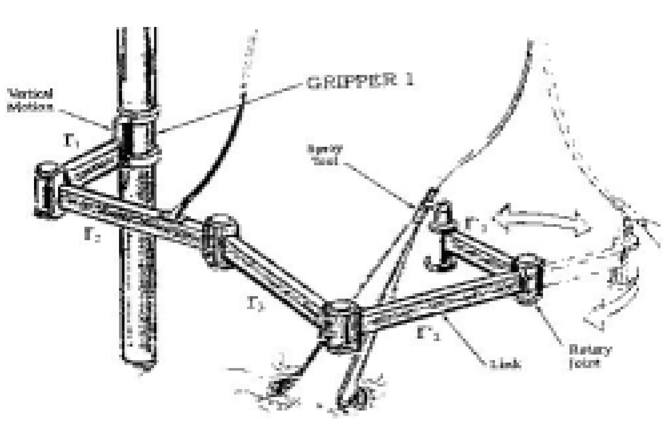


Fig. 3 Gripper 1 grasps the structural member in the tank

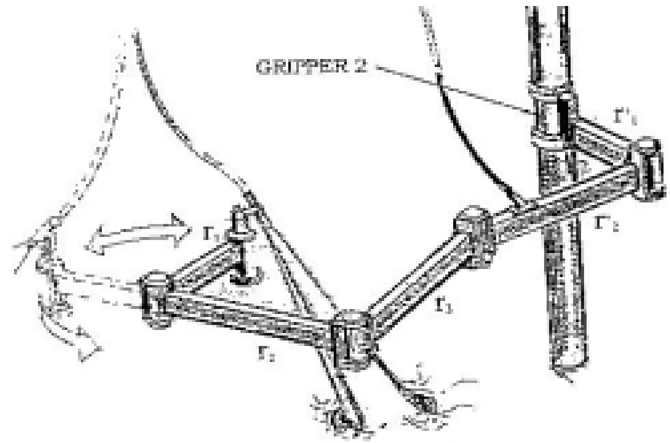


Fig. 4 Gripper 2 grasps the structural member in the tank

Based on the joint and link parameters assigned in figure 2, corresponding joint/link magnitudes and variables defined in C-B notation are listed in Table 1. The characteristic matrix $\mathbf{T}_i$ of each joint then can be derived in equation (1). Each $\mathbf{T}_i$ corresponds to the i*th* joint parameters listed in Table 1.

Table 1. Definition of joint parameters in C-B notation with gripper 1 relatively fixed

| Joint | $\theta_i$ | $h_i$ | $r_i$ | $\alpha_i$ | $\beta_i$ |
|---|---|---|---|---|---|
| 1 (R) | 0 | 0 | 36" | 0 | 0 |
| 2 (R) | ±135° | 0 | 12.125" | +90° | 0 |
| 3 (R) | §$\theta_3$ | 0 | 18.5" | 0 | 0 |
| 4 (R) | $-\theta_3$ | 0 | 12.125" | –90° | 0 |
| 5 (R) | ±135° | 0 | 36" | 0 | 0 |
| 6 (R) | ±135° | 0 | 36" | 0 | 0 |
| 7 (R) | ±135° | 0 | 36" | 0 | 0 |
| 8 (R) | 0 | 0 | 0 | 0 | 0 |

§ –25.622° *(VTM lower motion)*$\leq\theta_3\leq$+25.622° *(VTM lift motion)*

The orientation and position of gripper 2 relative to gripper 1, $x_1$-$y_1$-$z_1$, can be determined by

$$\mathbf{H} = \prod_{i=1}^{8} \mathbf{T}_i \qquad (3)$$

where $\mathbf{H}$ is the resultant 4x4 homogeneous matrix that specifies the orientation and position of gripper 2 relative to gripper 1, equation (2).

### 2.2. Gripper 2 grasps the structural member in the tank

Since there are two grippers in the RTD system and each operated independently, it is possible that gripper 2 grasps the structural member in the tank while gripper 1 performs the necessary task. Concept of the RTD system operated in this case is depicted in Fig. 4. The joint and link parameters defined in the 4x4 homogeneous C-B notation are listed in Table 2. With reference to Fig. 2, coordinate system $x_8$-$y_8$-$z_8$ will be the fixed frame of reference for this case.

The direction (orientation) and position of gripper 1 relative to gripper 2, $x_8$-$y_8$-$z_8$, can be calculated by

Table 2. Definition of joint parameters in C-B notation with gripper 2 relatively fixed

| Joint | $\theta_i$ | $h_i$ | $r_i$ | $\alpha_i$ | $\beta_i$ |
|---|---|---|---|---|---|
| 8 (R) | 0 | 0 | –36" | 0 | 0 |
| 7 (R) | ±135° | 0 | –36" | 0 | 0 |
| 6 (R) | ±135° | 0 | –36" | 0 | 0 |
| 5 (R) | ±135° | 0 | –12.125" | +90° | 0 |
| 4 (R) | §$\theta_4$ | 0 | –18.5" | 0 | 0 |
| 3 (R) | $-\theta_4$ | 0 | –12.125" | –90° | 0 |
| 2 (R) | ±135° | 0 | –36" | 0 | 0 |
| 1 (R) | 0 | 0 | 0 | 0 | 0 |

§ –25.622° *(VTM lift motion)*$\leq\theta_4\leq$+25.622° *(VTM lower motion)*

$$\mathbf{H_2} = \prod_{\substack{9-i \\ (i=1\rightarrow 8)}}^{1} \mathbf{T}_i \qquad (4)$$

where $\mathbf{H_2}$ is the resultant 4x4 homogeneous matrix that contains the numerical data of orientation and position of gripper 1 relative to gripper 2. $\mathbf{T}_i$ is the characteristic matrix derived in equation (1) corresponding to the i*th* joint parameters listed in Table 2.

## 3. DYNAMIC ANALYSIS AND SIMULATION

Three-dimensional solid model of the RTD system is generated in the Tele/IGRIP software package (Deneb Robotics, Inc.) according to the parameters specified in Fig. 2 and Tables 1 and 2. It is also simulated to obtain the dynamic data of joint forces and torques during operations. The dynamic data are acquired by actuating the RTD system along a trajectory defined by a set of “tag” points. Assumptions are made that gripper 1 (or gripper 2) moves in a constant linear velocity of 20 in/sec and carries a maximum payload of 110 lbs.

The two cases discussed in sections 2.1 and 2.2 are examined. First, the case that gripper 1 grasps the structural member and gripper 2 moves from tag point t1 (187, 0, 56.95) to t2 (20, -57.566, 56.95) by following a straight line trajectory on a surface with elevation Z=56.95" is simulated.

The motion of VTM is precluded in both cases. Next, to observe the effect of the VTM during operation, one nonlinear arbitrary trajectory defined by five tag points is selected with t1 (187, 0, 56.95), t2 (180.08, 34.657, 59.125), t3 (140.002, 80.865, 61.5), t4 (80, 92.417, 63.875) and t5 (0, 0, 66.25). In this case, gripper 2 grasps the structural member and gripper 1 follows the trajectory from t1 to t5 within a time span of 23 seconds. It should be noticed that both grippers 1 and 2 grasp the same structural member at the end of the motion.

Two additional cases are studied and simulated by exchanging gripper 1 and gripper 2 in the above cases. Consequently, the kinematic and dynamic behaviors of the RTD system are thoroughly investigated.

Both kinematic and dynamic (joint torques) data are analyzed and stored during the simulation by the Tele/IGRIP package. The Finite Difference Method (FDM) is used in Tele/IGRIP to determine the angular joint velocity and acceleration from already calculated angular joint positions. The governing equations of the FDM to compute joint velocity and acceleration are

$$\frac{\theta_i - \theta_{i-1}}{t_i - t_{i-1}} = \omega_i \quad (i = 2, 3, 4 \ldots\ldots\ldots\ldots\ldots\ldots) \qquad (5)$$

$$\frac{\omega_i - \omega_{i-1}}{t_i - t_{i-1}} = \alpha_i \quad (i = 3, 4 \ldots\ldots\ldots\ldots\ldots\ldots\ldots) \qquad (6)$$

If the initial time and angular position are defined as $t_1$ and $\theta_1$, apparently, joint velocity at the first tag point and joint accelerations at the first two tag points cannot be calculated.

## 4. NUMERICAL EXAMPLES

Although all four cases mentioned in the above section were analyzed, the first two examples are elaborated in the following.

Example 1: Gripper 1 grasps the structural member and gripper 2 moves from t1 (187, 0, 56.95) to t2 (20, –57.566, 56.95) in 18 seconds along a straight-line trajectory

The angular displacement, velocity, and acceleration of gripper 2 relative to joint 7 are shown in Figs. 5a to 5c. For the first half of the motion, gripper 2 rotates clockwise relative to joint 7 by increasing its magnitude to the limit of $-135^0$. Afterwards, gripper 2 starts decreasing in magnitude. The angular velocity decreases (in magnitude) to zero degree/second in the middle of the motion and then changes direction until its maximum angular velocity of 10 deg/sec is reached. Gripper 2 decelerates rapidly within the first 1.25 second and then gradually decelerates to stall within 18 seconds. Torque of joint 7 which connects to gripper 2 is shown in Fig. 6. It also decreases steeply in the first 1.25 second. The torque exerted on the structural member is presented in Fig. 7.

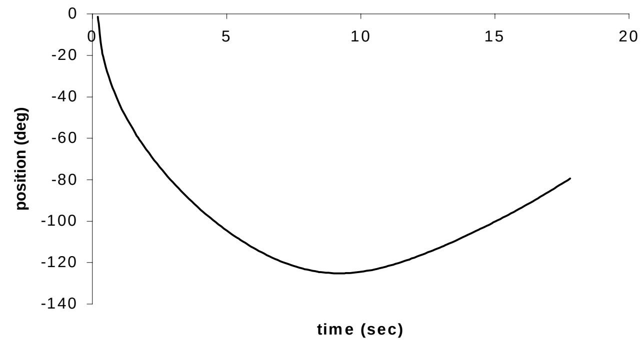


Fig. 5a Gripper 2 angular displacement relative to joint 7

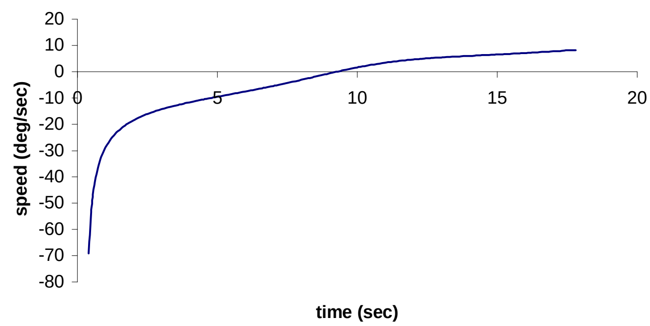


Fig. 5b Gripper 2 angular velocity relative to joint 7

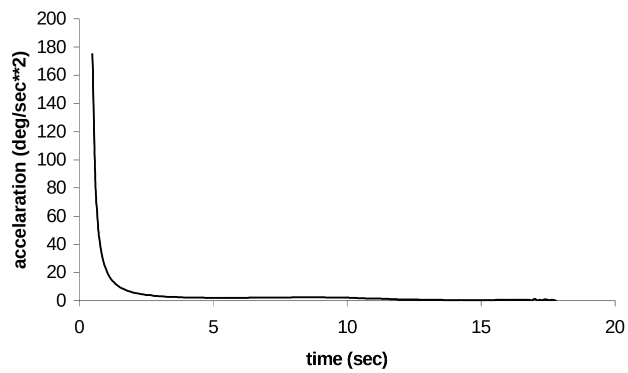


Fig. 5c Gripper 2 angular acceleration relative to joint 7

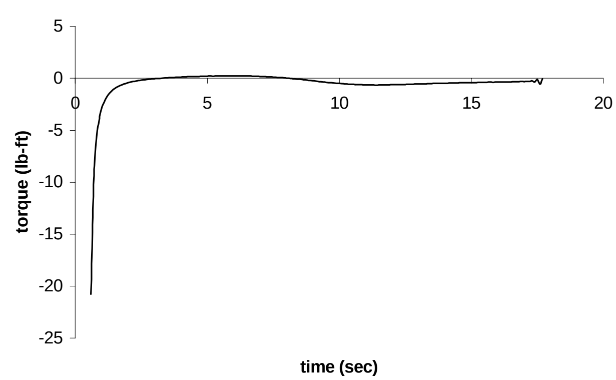


Fig. 6 Torque of joint 7

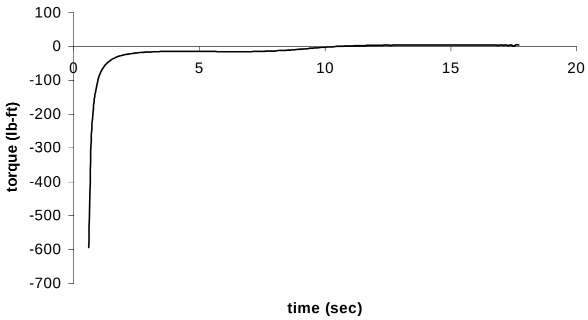


Fig. 7 Torque exerted on the structural member

<u>Example 2:</u> <u>Gripper 2 grasps the structural member and gripper 1 moves nonlinearly from tags t1 to t5 *(see Section 3)* in 23 seconds to grasp the same structural member</u>

Analytical results of angular kinematics of gripper 1 with respect to joint 2 are shown in Figs. 8a to 8c.

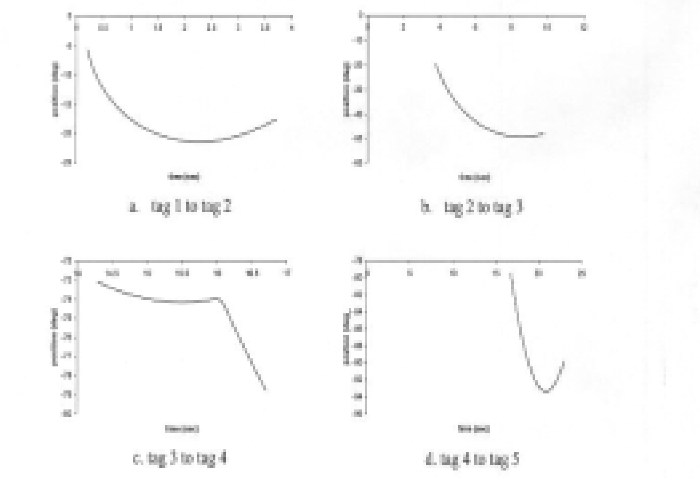


Fig. 8a Gripper 1 angular displacement relative to joint 2

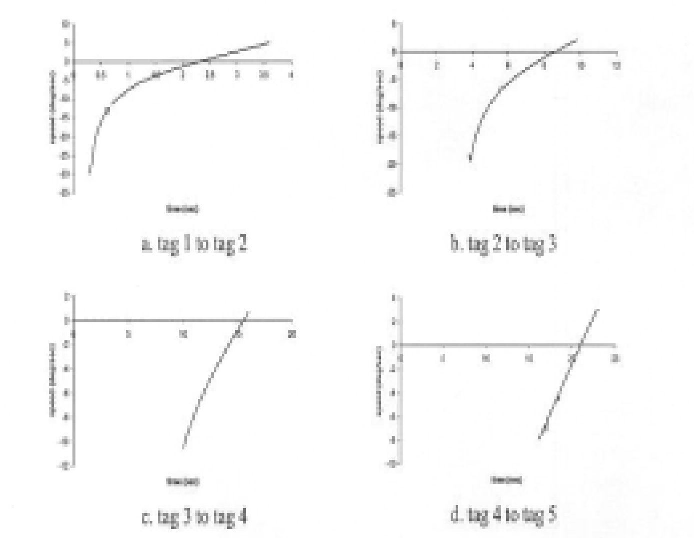


Fig. 8b Gripper 1 angular velocity relative to joint 2

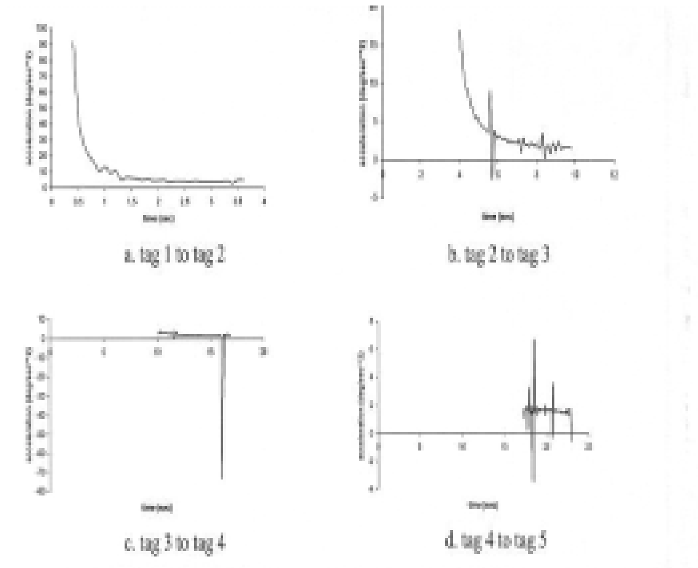


Fig. 8c Gripper 1 angular acceleration relative to joint 2

Discontinuities appear in the curves may be caused by small time interval ($\Delta t$=0.1 sec) used for FDM in Tele/IGRIP. Any discontinuous points in the curve should be interpolated with adjacent points to follow the general trend of the curve. Torque of joint 2 that connects to gripper 1 is given Fig. 9.

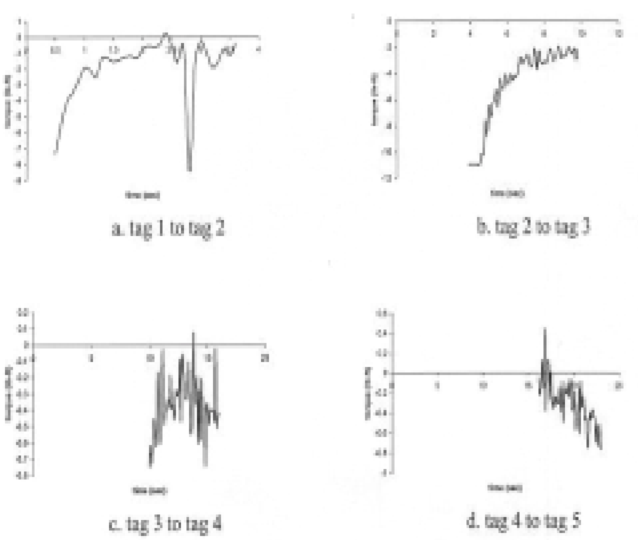


Fig. 9 Torque of joint 2

The VTM elevates gripper 1 from 56.95" to 66.25" so that the RTD system can grasp the same structural member with both grippers. Torque of the VTM during the motion is illustrated in Fig. 10. At last, the torque applied to the structural member from gripper 2 decreases in magnitude as expressed in Fig. 11.

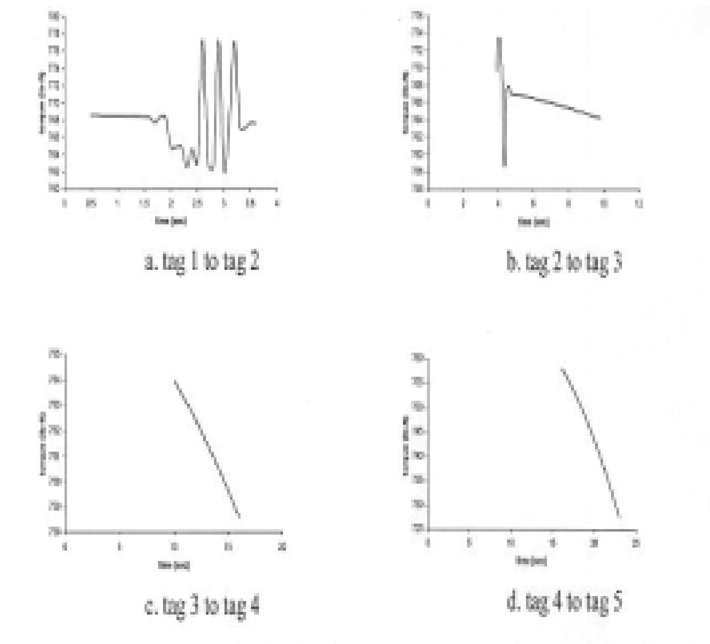


Fig. 10  Torque of the VTM

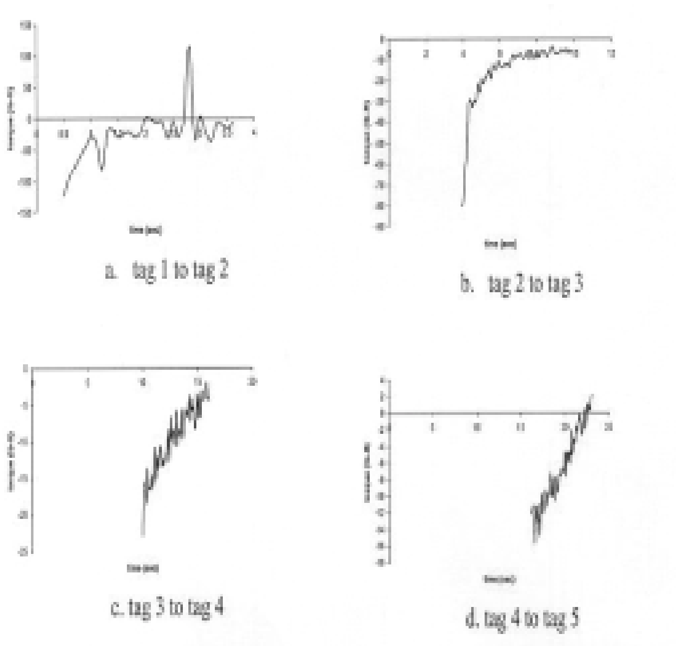


Fig. 11  Torque exerted on the structural member

## 5. CONCLUSION

In this paper, kinematic modeling in C-B notation, kinematic analysis, and dynamic analysis have been carried out successfully for a special dual-gripper Remote Tool Delivery (RTD) manipulator operated as an open-chain robotic system. The dual-gripper design and the inclusion of a VTM (Vertical Translation Mechanism) distinguish the RTD system from other ordinary robotic systems. These special features provide greater dexterity and flexibility; yet, increase the complexity in modeling and analysis. Two possible operating configurations were analyzed and simulated using the Tele/IGRIP virtual reality package. Two out of four example cases were illustrated in this paper.

The most appropriate operating configurations can be determined by the operator based on a comparison table generated using the calculated kinematic (displacement, velocity and acceleration) and dynamic (joint torque) data. Of course, the data will be comparable only when the same trajectory is followed by gripper 1 (gripper 2 relatively fixed) and gripper 2 (gripper 1 relatively fixed), respectively. This table records the minimum and maximum joint kinematics and dynamics during the entire motion of the RTD system. Operator selects the feasible operating configuration according to the priorities set up for a particular operation. For instance, the priority can be maximizing the operating speed, minimizing the torque exerted on the structural member, or minimizing the energy consumption.

## 6. ACKNOWLEDGEMENT

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