

# Dual Quaternion Based Control

## ED6006: Advanced Topics in the Mechanics of Robots

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### 1 Introduction

#### 1.1 Why use quaternions?

The following are a few issues using the conventional methods of representation of a rigid body:

1. Well known reason of representation singularities using Euler Angles (Gimbal Lock)
2. The rotation matrices have inherent problems. The rotational part of the transformation matrix is orthogonal, but they drift and cause for unwanted scaling and shearing the object of interest in a computer graphics situation[1]. Re-normalisation of these matrices is not a simple method
3. Quaternions are good for another reason that they preserve the algebraic nature of the equations derived from them. They do not produce a complicated set of equations in sines and cosines
4. Interpolation of matrices is not straightforward

##### 1.1.1 Quaternions

A short description of quaternions is given below.

Quaternion, introduced by Hamilton are four dimensional extensions to the complex numbers we know of. It is represented as,

$$\mathbf{q} = a_0 + a_1i + a_2j + a_3k \quad (1)$$

where  $a_0, a_1, a_2, a_3 \in \mathbb{R}$  and  $i, j, k$  are the imaginary components and are defined as,

$$i^2 = j^2 = k^2 = -1 \quad (2)$$

$$ij = k, jk = i, ki = j, ji = -k, kj = -i, ik = -j \quad (3)$$

Another common representation of quaternions is as a scalar and a vector pair as shown,

$$\mathbf{q} = (s, \vec{v}) \quad (4)$$

The addition of two quaternions follows the normal element wise operation, where as multiplication is as follows,

$$\mathbf{q}_1 \mathbf{q}_2 = (s_1 s_2 - \vec{v}_1 \vec{v}_2, s_1 \vec{v}_2 + s_2 \vec{v}_1 + \vec{v}_1 \times \vec{v}_2) \quad (5)$$

The conjugate of a quaternion and the norm are as defined,

$$\mathbf{q}^* = (s, -\vec{v}) \quad (6)$$

$$\|\mathbf{q}\| = \mathbf{q} \mathbf{q}^* \quad (7)$$

Unit quaternions, i.e.  $\|\mathbf{q}\| = 1$  can be used to represent rotations. Given rotation of a rigid body by an angle  $\theta$  about an axis  $\vec{k}$  it can be represented as,

$$\mathbf{q} = (\cos(\frac{\theta}{2}), \vec{k} \sin(\frac{\theta}{2})) \quad (8)$$

An other useful property of quaternions are the Hamiltonian operators. For a given quaternion represented as (1), the Hamiltonian operators are as given [2],

$${}^+ \bar{H}(\mathbf{q}) = \begin{pmatrix} a_0 & -a_1 & -a_2 & -a_3 \\ a_1 & a_0 & -a_3 & a_2 \\ a_2 & a_3 & a_0 & -a_1 \\ a_3 & -a_2 & a_1 & a_0 \end{pmatrix} \quad (9)$$

$${}^- \bar{H}(\mathbf{q}) = \begin{pmatrix} a_0 & -a_1 & -a_2 & -a_3 \\ a_1 & a_0 & a_3 & -a_2 \\ a_2 & -a_3 & a_0 & a_1 \\ a_3 & a_2 & -a_1 & a_0 \end{pmatrix} \quad (10)$$

These operators allow us to manipulate the quaternion multiplication as though they are commutative.

$$\mathbf{q}_1 \mathbf{q}_2 = {}^+ \bar{H}(\mathbf{q}_1) \mathbf{q}_2 = {}^- \bar{H}(\mathbf{q}_2) \mathbf{q}_1 \quad (11)$$

## 1.2 Why use dual numbers?

The reasons for using dual numbers for representation in robot kinematics are,

1. Allows us to do line transformations.
2. Gives a compact representation of both translation and rotation components, and their velocities, which are represented by a line in the 3D space.

### 1.2.1 Dual Numbers

Given the distance between two lines in 3D as,  $d$  and the angle their directions is  $\alpha$ ,

$$\hat{\alpha} = \alpha + \epsilon d \quad (12)$$

where  $\epsilon^2$  is defined to be 0

### 1.3 Why use dual quaternions?

This is a generalisation of a quaternion into a dual number. They carry the advantages of both using quaternions and dual numbers.

Unit dual quaternions can be used to represent general affine transformations. and are represented as below,

$$\hat{\mathbf{q}} = \mathbf{q} + \frac{\epsilon}{2} \mathbf{t} \mathbf{q} \quad (13)$$

where  $\mathbf{q}$  represents the quaternion corresponding to the rotation,  $\mathbf{t}$  represents the quaternion representing translation i.e.,  $(0, \vec{t})$ , where  $\vec{t}$  represents the translation vector and  $\hat{\mathbf{q}}$  represents the configuration of a rigid body translated by  $\mathbf{t}$  and then rotated by  $\mathbf{q}$ .

## 2 Dual Quaternion Control

The following method of formulating control law using dual quaternions is as given in [3]

### 2.1 Forward Kinematics

The robot used in the current study is the six axis, PUMA 560 robot. The forward kinematic map in terms of the end-effector dual quaternion is obtained based on the DH parameters given in [4]

$$\hat{\mathbf{q}}_{ee} = \hat{\mathbf{q}}_1 \hat{\mathbf{q}}_2 \hat{\mathbf{q}}_3 \dots \hat{\mathbf{q}}_n \quad (14)$$

where,  $\hat{\mathbf{q}}_1$  represents the configuration of the end-effector and the other represent the individual quaternions corresponding to the DH parameters.

### 2.2 Formulating Jacobian

From here we assume the dual quaternions are mapped to the  $\mathbb{R}^8$ . So we differentiate the eight dimensional tuple with respect to the actuated variables, i.e.  $\boldsymbol{\theta}_1, \boldsymbol{\theta}_2, \boldsymbol{\theta}_3, \boldsymbol{\theta}_4, \boldsymbol{\theta}_5, \boldsymbol{\theta}_6$ . This gives us a Jacobian of size  $8 \times 6$  which we shall call  $J_{dual}$ . This gives us,

$$\dot{\hat{\mathbf{q}}} = J_{dual} \dot{\boldsymbol{\theta}} \quad (15)$$

## 2.3 Control Law

Here we only deal with a regulation problem using Jacobian based control. A regulation problem is nothing but a position control problem, i.e. given a position or a final configuration, we control the robot to reach that final position. In this case this is done based on the Jacobian, i.e. the problem is simplified by considering only the kinematics ignoring the dynamic effects of the robot.

### 2.3.1 Error Dynamics

Let the initial configuration of the end-effector be  $\hat{\mathbf{q}}_1$  and the desired configuration to be  $\hat{\mathbf{q}}_d$ . Let us define the error to be,

$$\hat{\mathbf{q}}_e = \hat{\mathbf{q}}_d - \hat{\mathbf{q}} \quad (16)$$

where  $\hat{\mathbf{q}}_e$  represents the error dual quaternion and  $\hat{\mathbf{q}}$  represents the configuration at any given instant.

Differentiating equation (16), gives the following,

$$\dot{\hat{\mathbf{q}}}_e = \dot{\hat{\mathbf{q}}}_d - \dot{\hat{\mathbf{q}}} \quad (17)$$

Since, we are dealing with a regulation problem, we have a fixed  $\dot{\hat{\mathbf{q}}}_d$  and hence its derivative is zero.

$$\dot{\hat{\mathbf{q}}}_e = -\dot{\hat{\mathbf{q}}} \quad (18)$$

Substituting (15) equation in (18) gives,

$$\dot{\hat{\mathbf{q}}}_e = -J_{dual}\dot{\vec{\theta}} \quad (19)$$

Let us consider a proportional control of this system and propose the control law to be,

$$\dot{\vec{\theta}} = J_{dual}^T K \hat{\mathbf{q}}_e \quad (20)$$

This choice is to ensure asymptotic stability of the system making  $J_{dual}J_{dual}^T$  a positive definite matrix[3].

This gives the error dynamics to be,

$$\dot{\hat{\mathbf{q}}}_e + J_{dual}J_{dual}^T K \hat{\mathbf{q}}_e = 0 \quad (21)$$

Integrating the equations (21) and (20) together gives us the motion of the end-effector.

### 3 Discussion

The gain parameter  $K = 185$  is tuned to for the performance parameters of settling time of 10 seconds.

The asymptotic convergence of the error is as shown,

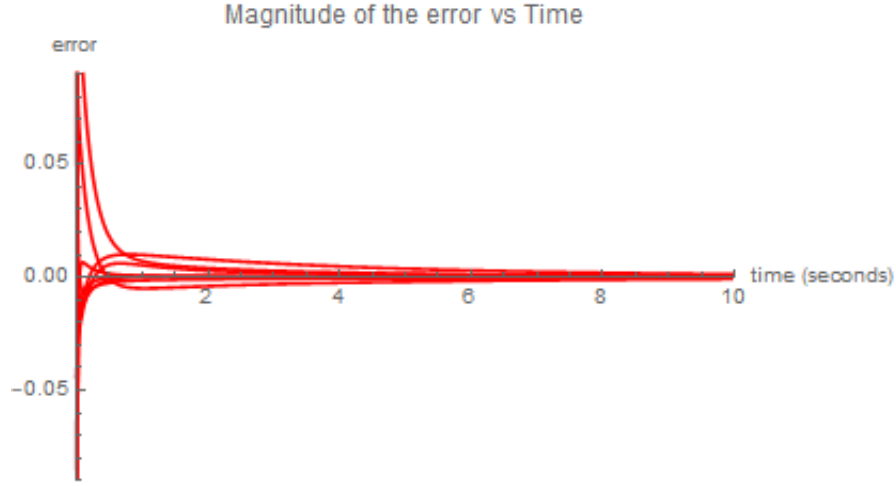


Figure 1: Asymptotic convergence of the quaternion error

The corresponding plot of the angles reaching the final position is as shown, With increase in

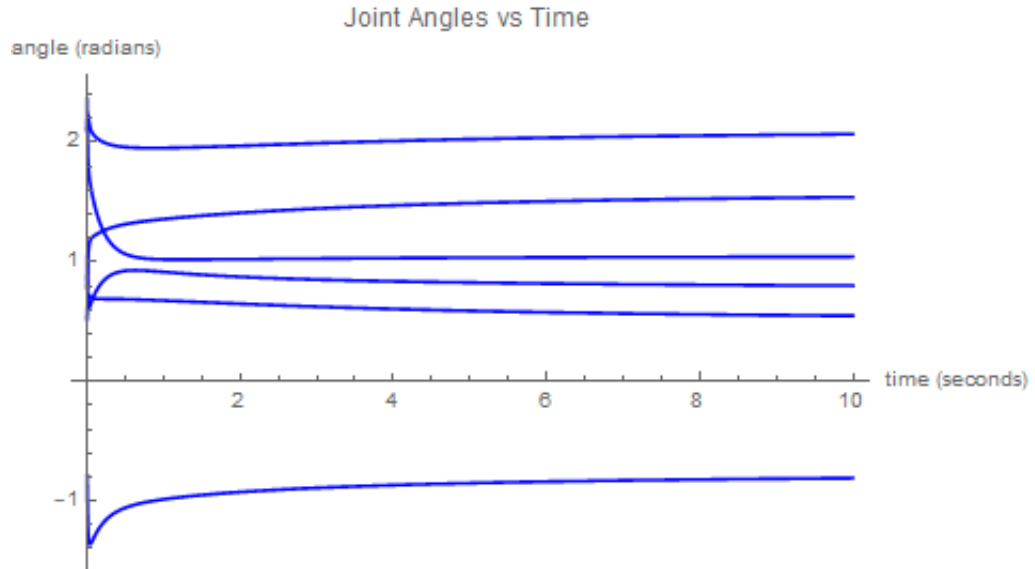


Figure 2: The trajectory of the six angles of PUMA 560 robot

the gain as expected the manipulator tries to minimise the error more aggressively.

### 4 Utility

One of the application for such dual quaternion based control could be in cooperative task space, where two robot arms need to move together to perform a task [5].

When two robots or a single robot with two hands do a task, using dual quaternions to represent the task would greatly simplify the task definition. The paper has suggested the usage of various primitives for control. These primitives used in any sequence would give meaningful control to complete the task.

One of such primitive is the task definition of relative Cartesian position control which is demonstrated here. Consider the relative quaternion of the end effector to be,

$$\hat{\mathbf{q}}_r = \hat{\mathbf{q}}_2^* \hat{\mathbf{q}}_1 \quad (22)$$

$$\hat{\mathbf{q}}_r = \mathbf{q}_r + \mathbf{q}_r' \quad (23)$$

$$\mathbf{q}_r' = \frac{\epsilon}{2} \mathbf{t}_r \mathbf{q}_r \quad (24)$$

Now from this the translation quaternion can be extracted out as,

$$\mathbf{t}_r = 2\mathbf{q}_r' \mathbf{q}_r^* \quad (25)$$

Again consider the quaternion to be  $\mathbf{t}_r$  to be an element in  $\mathbb{R}^8$ . Differentiating this equation gives and using (11),

$$\dot{\mathbf{t}}_r = 2\dot{\mathbf{q}}_r' \mathbf{q}_r^* + 2\mathbf{q}_r' \dot{\mathbf{q}}_r^* \quad (26)$$

$$\dot{\mathbf{t}}_r = 2(\bar{H}(\mathbf{q}_r^*)J_{\mathbf{q}_r'} + H^+(\mathbf{q}')J_{\mathbf{q}_r^*})\dot{\boldsymbol{\theta}} \quad (27)$$

where  $\dot{\boldsymbol{\theta}}$  here represents a 12 dimensional vector. So controlling the relative translation quaternion which is 4 dimensional gives us the definition of control for all the joint angles.

The similar strategy was used in [5] with four different primitives to perform simple tasks like grasping a balloon and pouring water in a cup from a bottle with a two armed robot. Using this new definition of Jacobian for the given task we implement the control strategy as mentioned in the section 2.3.

The following is the asymptotic error convergence plot and the corresponding change in the angles of both the manipulators.

**VISUALISATION OF THE MOTION INSERT PLOTS HERE**

## 5 Error in the error!

Based on the (brief) literature survey of usage of dual quaternions done, it is observed that in practical purposes it is comfortable to implement control assuming that these dual quaternions are embedded in  $\mathbb{R}^8$  as in [3] and [5]. But we know that these entities actually represent elements from  $\mathbb{SE}(3)$  and hence difference between the two values does not yield a distance measure.

## 5.1 Are we just lucky?

So the question here is, are we getting lucky with this method? If not why does it work?

No, the reason for why this works can be seen from [6], which talks about the distance measures in  $\mathbb{SO}(3)$  and  $\mathbb{SE}(3)$ . From the fact that there is no "distance" measure that can be defined in  $\mathbb{SE}(3)$  we have a lot more freedom to define a way to measure distance ignoring the physical considerations. One of such metric is the one we constructed previously, i.e. the difference between quaternions. Similarly various other measures have been proposed based on the requirement. Simple difference of quaternions in [5], measure based on the required performance criteria for robust control in [7] etc.

## 5.2 What do we do?

For this particular work we follow the path of [8], which beautifully extends the classical PD controllers to  $\mathbb{SO}(3)$  and  $\mathbb{SE}(3)$ .

Following the formulation given in [8], we choose to use the logarithmic feedback controller. The setting given in the paper is generic to any system in  $\mathbb{SE}(3)$  and an example in  $\mathbb{SE}(2)$  of a differential mobile robot is given. In the current work, we extend this formulation to dual quaternions and show its utility in control of a six axis serial robot.

# 6 Error Dynamics

Now that we know the fact that dual quaternions represents elements in  $\mathbb{SE}(3)$ , a more reasonable choice of error would be,

$$\hat{\mathbf{q}}_e = \mathbf{q}_d^* \hat{\mathbf{q}} \quad (28)$$

Differentiating the above term and setting  $\dot{\mathbf{q}}_d^*$  to zero(regulation problem), we get,

$$\dot{\hat{\mathbf{q}}}_e = \mathbf{q}_d^* \dot{\hat{\mathbf{q}}} \quad (29)$$

The logarithmic error feedback in our case would be of the form,

$$\dot{\hat{\mathbf{q}}} = -K \log(\hat{\mathbf{q}}_e) \quad (30)$$

where K is a matrix positive definite matrix. Unlike the previous case, in this case, we can tune the gains for linear and angular velocities separately by internally having different coefficients in the matrix.

There are some interesting properties of a dual quaternion. Similar to any complex number which

can be represented using the Euler's form, dual quaternions can be represented in a similar way [9].

$$\hat{\mathbf{q}} = \mathbf{q} \exp(\epsilon \frac{\vec{t}}{2}) \quad (31)$$

So applying a logarithm would give us the following,

$$\log(\hat{\mathbf{q}}) = \frac{\boldsymbol{\theta} \vec{k}}{2} + \epsilon \frac{\vec{t}}{2} \quad (32)$$

Using the above equations, we reformulate the error dynamics in terms of the elements in  $se(3)$  and implement control over these elements.

**Note:** Please understand that,

$$\log(\hat{\mathbf{q}}) = \log(\hat{\mathbf{q}}_1 \hat{\mathbf{q}}_2) \quad (33)$$

satisfies but,

$$\log(\hat{\mathbf{q}}) \neq \log(\hat{\mathbf{q}}_1) + \log(\hat{\mathbf{q}}_2) \quad (34)$$

$$\log(\hat{\mathbf{q}}) - \log(\hat{\mathbf{q}}_1) \neq \log(\hat{\mathbf{q}}_2) \quad (35)$$

This is from the fact that dual quaternions multiplication is not same as multiplication in  $\mathbb{R}^n$ . Instead we have to do,

$$\log(\hat{\mathbf{q}}_1^* \hat{\mathbf{q}}) = \log(\hat{\mathbf{q}}_2) \quad (36)$$

## 7 Discussion

The error in the controlled entities i.e., the error in end effector orientation and the position asymptotically go to zero.

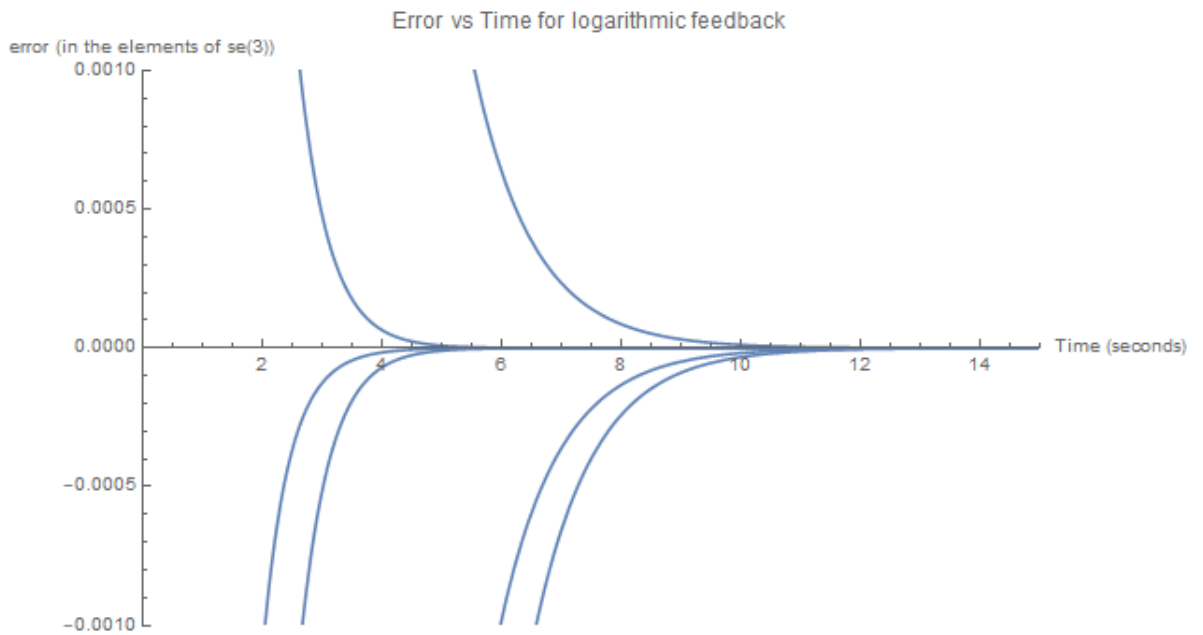


Figure 3: Asymptotic convergence of the error for logarithmic feedback



The proportional gain of both the linear and angular velocity components was kept equal to 1 for the above plot.

## 8 Observations

The following are a few quick observations from the above results.

1. The first thing to notice is how three errors go to zero quickly than the ones in angle. The ones that converge quickly are the ones corresponding to the errors in the translation of the end-effector.
2. For a given performance parameters, it is seen that the logarithmic feedback requires much smaller gains, 1 vs 185 than the error formulated by the difference in the quaternions

## 9 Comparison of the two controllers

Both the controllers were given the same desired and final quaternion configurations and the resulting control laws are observed. Please note that for fair comparison, the gains of both the controllers is fixed to a constant value, which is the average of the current values. We shall call the logarithmic controller as logc and difference controller as diffc from now on.

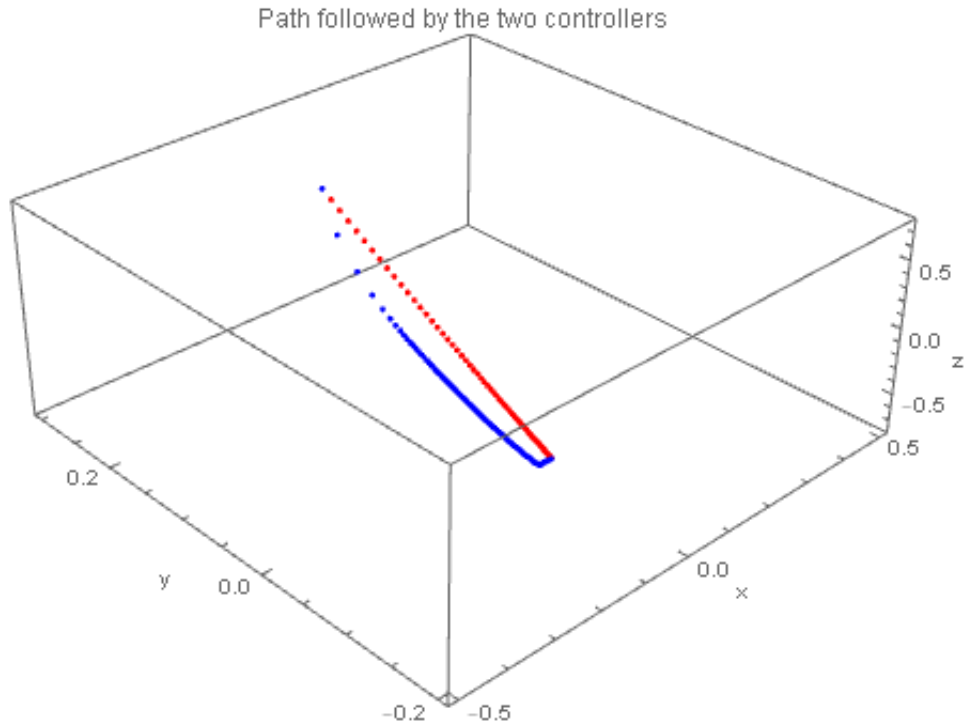


Figure 4: Path traced by the logarithmic controller (red) and the difference controller(blue)

where the three axes represent  $\mathbb{R}^3$ .

Note that `diffc` travels extra distance than the `logc`. Investigating the path followed by `diffc` alone would be as shown below.

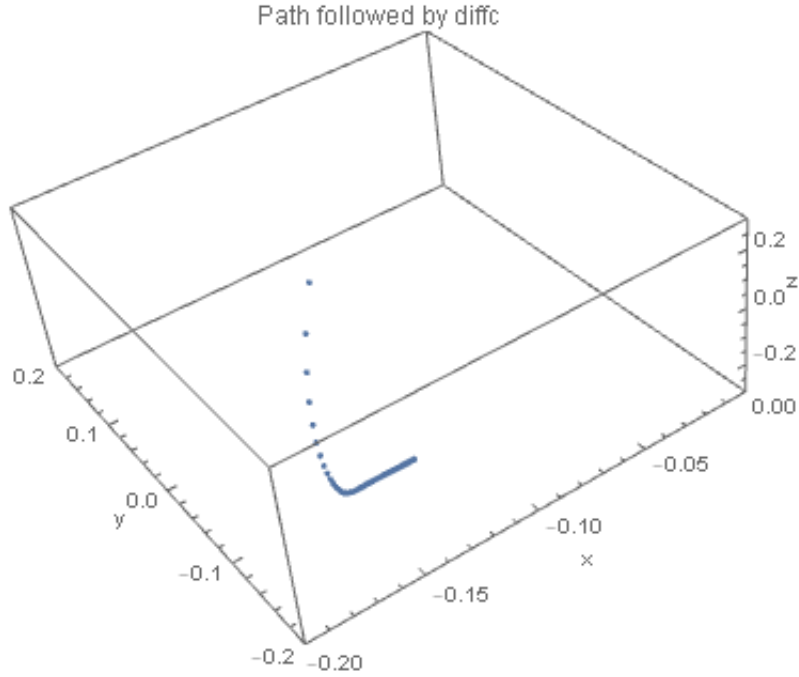


Figure 5: Curved path traced by `diffc`

The animations in the accompanying Mathematica notebook would further let us visualise the complete  $\mathbb{SE}(3)$  motion than the  $\mathbb{R}^3$  motion. One can easily observe that the motion of logarithmic controller is arguably more "natural". I come to this conclusion after observing myself and a few of my friends manipulate everyday things. You can try it out yourself!

## 10 Concluding question

Taking this discussion a step further ignoring the internal actuation, dynamics, structure of the hand, I ask the following question,

**Our eyes cannot perceive  $\mathbb{SE}(3)$  but can our brains do?**

## 11 Things not told

The following are the questions and discussion left for the future.

1. There is yet another way to describe error. That is by splitting the  $\mathbb{SO}(3)$  and  $\mathbb{R}^3$  parts of the dual quaternion and follow geodesics in each of these space. This approach is called the Double Geodesic Control, which we have not described here.

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