On the Effort of Task Completion for Partially-Failed Manipulators

Hamid Abdi, Member IEEE
Centre for Intelligent Systems Research
Deakin University, VIC 3217, Australia
Hamid.Abdi@deakin.edu.au

Saeid Nahavandi, SMIEEE
Centre for Intelligent Systems Research
Deakin University, VIC 3217, Australia
Saeid.Nahavandi@deakin.edu.au

Zoran Najdovski, Member IEEE
Centre for Intelligent Systems Research
Deakin University, VIC 3217, Australia
Zoran.Najdovski@deakin.edu.au

***Abstract*—Adding to a previous work of the authors for task completion for partially failed manipulator, other aspects of the effort are discussed. The paper aims to investigate on the strategies of maximum effort for maintaining the availability of partially failed manipulators. The failures are assumed as the joint lock failures of the manipulators. The main objective is to facilitate the existing manipulators to continue their tasks even if a non catastrophic fault occurs into their joints. The tasks includes motion tasks and force tasks. For each group of tasks a constrained optimality problem is introduced. Then in a case study a required force profile on a desired trajectory using a 3DOF planar manipulator is indicated. Through this study the joint angles and joint torques for a healthy manipulator and a faulty manipulator are shown. It is illustrated that a failure in the second joint is tolerated on the trajectory of end-effector.**

Index Terms *Fault tolerant, Robotic manipulators, fault tolerant motion, fault tolerant force, Constraint Primitives, kinematic redundancy.*

I. INTRODUCTION

Maintaining the availability of the manipulators is critical for some tasks such as handling of hazardous material[1] and space applications[2]. Fault tolerance and optimally fault tolerance for robotic manipulators have received a great attention in last two decades by the robotics research community. The starting point was the study on the availability of the robotic manipulators for space shuttle [3]. Within the literature, different solutions have been discussed to improve the reliability of robotic manipulators, including reliability analysis of the manipulators and its parts, redundancy in the actuators, kinematically redundant manipulators, parallel manipulators and cooperative manipulators [4-5]. Beside, fault tolerant control has been widely studied for fault analysis, fault identification and isolation and failure recovery strategies for robotic manipulators[6]. Basically two approaches exist for fault tolerant control. The first is classic approach and the second is artificial intelligence approach. For instance the robust adaptive control proposed in [7] and fuzzy or neural network base solution in [8] are two studies for fault tolerant control of robotics manipulator. Within all of these works, improving the functionality of the robotic manipulators under various internal and external constraints is addressed. Providing the capability to complete their tasks in all aspects of the operation of the manipulator when the manipulator posses a partial fault, directly increases the availability of the manipulator.

The fault tolerant operation of the manipulators consist different problems based on their task. There is hard limitation for full failure recovery especially when no redundancy is available or the available redundancy is not effectively used for accomplishing the tasks. Full fault recovery and optimality of the post failure operation are still challenging problem in robotics community, especially if a general task is considered. It is required to identify the tasks and then formulize a problem for each group of similar tasks. However because of the limitation, it commonly happens that the full fault recovery to be not possible. In these cases having an optimal output may be acceptable. For example if the manipulator needs to continue its task even if a joint locked failure happens. Then maybe an optimal action of the manipulator is applicable. Therefore finding the optimal action of the manipulator is required.

The author has done a series of study on fault tolerant operation of robotics manipulators. In each study a part of the problem was analysed. But each work seems lacking from the other aspects of the fault tolerance. The aim of this study is to put to gather all those studies for different aspects of the fault tolerance for a robotic manipulator. And provide a general fault tolerant operation for a given task. Therefore the tasks of the manipulators are categorized into motion and force task in different groups and the constrained optimality problem for each groups is formulized. Then the hardest case is used to tolerate a fault for a case study problem.

The remainder of the paper is organized as follows. After the introduction in section II, the basic definitions are presented in section III. Then an effort to tolerate a locked joint failure of the robotics manipulators is addressed for different tasks and an optimality problem is formulized for each task in section IV and V. Then in section VI an optimal fault recovery for a 3DOF manipulator is indicated through a case study. In this case study a desired trajectory, desired velocity profile and a desired force profile are provided using a healthy and a faulty manipulator and the results are compared in section VI. Finally the concluding remarks are indicated.

II. Basic definitions

Robotic manipulators are used to handle or manipulate objects through movement or applying a force. Therefore basically two types of tasks are recognized for the manipulator. The first category is called motion tasks and the second category is called force tasks. In the motion tasks only the movement of the manipulator is interested and they are grouped into:

1- Point to point motion tasks on an arbitrary trajectory
2- Desired trajectory tasks

In the force tasks, the force provided at the end-effector (EEF) of the manipulator is interested. Similar to motion tasks, they are divided into following groups:

1- Fixed point force tasks
2- Force profile alongside a point to point on an arbitrary trajectory tasks
3- Force profile alongside a desired trajectory tasks

This paper aims to briefly answer the aforementioned questions. Therefore each group is addressed in the remainder of the paper.
In a preliminary work on the effort of task completion for partially failed manipulator, only the first problem was addressed in detail in [9]. Where the problem is formulized based on constraint primitives and inferring of constraint primitives form the joint failures. In this paper the problem for each group of the aforementioned categories is formulated they the hardest one is applied for a case study.

III. Efforts on fault tolerance motion for partially failed manipulator

A. Point to point motion tasks on an arbitrary trajectory

If a manipulator is required to move from a source point to a destination point and if the trajectory of the manipulator is an arbitrary trajectory, then the redundancy is available for its trajectory. This can be used to tolerate a partial failure of the manipulator [9]. Briefly If $T(x, y, z, t)$ is a trajectory which starts from R_s it ends to R_d. If the two points are in the manipulator workspace excluding the prohibited region, then a manifold exists for the trajectory. If a failure occurs into one or more joints of the manipulator, one idea is to infer a new geometric constraint set based on the post failure workspace analysis. If the failure of the manipulator is locked joint failure then the faulty manipulator is called reduced manipulator. The post failure workspace can be called reduced workspace. Then exclude the prohibited regions within the reduced manipulator workspace due to the obstacles. This gives a manifold for the trajectory planning for faulty manipulator. Then a new constrained primitive set is used to find a new trajectory for the faulty manipulator. At this stage it is assumed that the trajectory planner is available. Therefore if the new set of the constraints is provided and the current and destination points are given then the planner tries to propose a new trajectory. The new trajectory tolerates the failure.
This has to be noted that a failure limits the workspace of the manipulator and the destination point may occur to be outside of the reduced workspace. Therefore there is no way to tolerate. However if an optimal behaviour is desired then the closest point to the destination point of the task is defined as optimality condition in Eq.(1)

$$Min \quad \left| R(x, y, z, t_f) - R_d \right| \qquad \text{Eq.(1)}$$

where $\left| R(x, y, z, t_f) - R_d \right|$ is the final distance between the end-effector position and the destination point.

To solve this problem if it is assumed that the constraints prior the failure and after the failure are known. In the literature search methods including genetic algorithm [10] or the potential field [11] can be used to complete the task even with the faulty manipulator. Figure 1 is showing a Simulink model for used to test this strategy [9].

B. Desired trajectory tasks and faults tolerance

In this case the faulty manipulator tries to maintain its desired trajectory even in a degraded mode. A comprehensive study has been done by the author in [12]. And it is shown that the problem can be solved using minimum velocity jump concept. In minimum velocity jump the velocity of the EEF of the manipulator must be maximally close to the desired velocity on its desired trajectory. However in general a slower speed after failure is acceptable. Therefore the main constraint is minimum velocity jump obtained from the norm-2 of the velocity jump vector Eq.(2):

$$Min \quad \left| \lambda V - \hat{V} \right| \qquad \text{Eq.(2)}$$

where V is the desired velocity of the EEF and $\hat{V}$ is the velocity of the EEF after failure. and $0 \le \lambda \le 1$ is a scaling factor.

In this case the failure is tolerated if the trajectory remains in the post failure workspace of the manipulator. And a zero velocity jump is achieved if the Jacobian of the reduced manipulator remains full rank for all the points on the trajectory.

IV. Efforts on Fault Tolerance Force for Partially Failed Manipulator

In this section the problem for each groups of the force task is formulated. The manipulator force is the EEF force which is a function of joint torques and the dynamics of the manipulator.

A. Fixed point force

If the manipulator is not moving while it is holding an object or it is applying a force then if a failure occurs into one of the joints. The fault tolerance is achieved if the EEF post failure force is equal to the force prior to the failure.

Therefore the strategy is to find a set of new torque for the joints to maintain the force of the EEF. This is formulized by using a minimum force jump in Eq.(3)

$$Min \quad \left|\mu F - \hat{F}\right| \qquad \text{Eq.(3)}$$

where F is the desired force of the EEF and $\hat{F}$ is the post failure EEF force. Similar to Eq.(2) $0 \le \mu \le 1$ is a force scaling factor.

This optimality gives a new joint torques to maintain the force F.

B. Force profile on an arbitrary trajectory

In this case the manipulator is providing a specific force on an arbitrary trajectory. For instance carrying a load between two points. The fault tolerant operation is achieved if a new trajectory can be found in which the force jump on any point of the new trajectory is zero. An optimality problem for this case is as Eq.(4) and Eq.(5)

$$Min \quad \left|R(x, y, z, t_f) - R_d\right| \qquad \text{Eq.(4)}$$

$$\left|\mu F - \hat{F}\right| = 0 \qquad \text{Eq.(5)}$$

where $\left|R(x, y, z, t_f) - R_d\right|$ is the final distance between the end-effector position and the destination point. F is the desired force of the EEF and $\hat{F}$ is the post failure EEF force. $0 \le \mu \le 1$ is a force scaling factor.

Similar to the corresponding problem in motion task, it is only achieved when the desired point remains in the workspace of the manipulator and required force can be provided by the remained healthy joints.

C. Force task on a desired trajectory

In this case both the trajectory and the force along the trajectory should be maintained. For example manipulator is applying a force for a given trajectory. Therefore the minimum velocity jump and minimum force jump are required. Generally, this problem has hard limits but still can be achieved if enough kinematic redundancy is available even after failure. The optimality problem for this case is introduced as Eq.(6) and Eq.(7) which is a multi-objective optimization problem

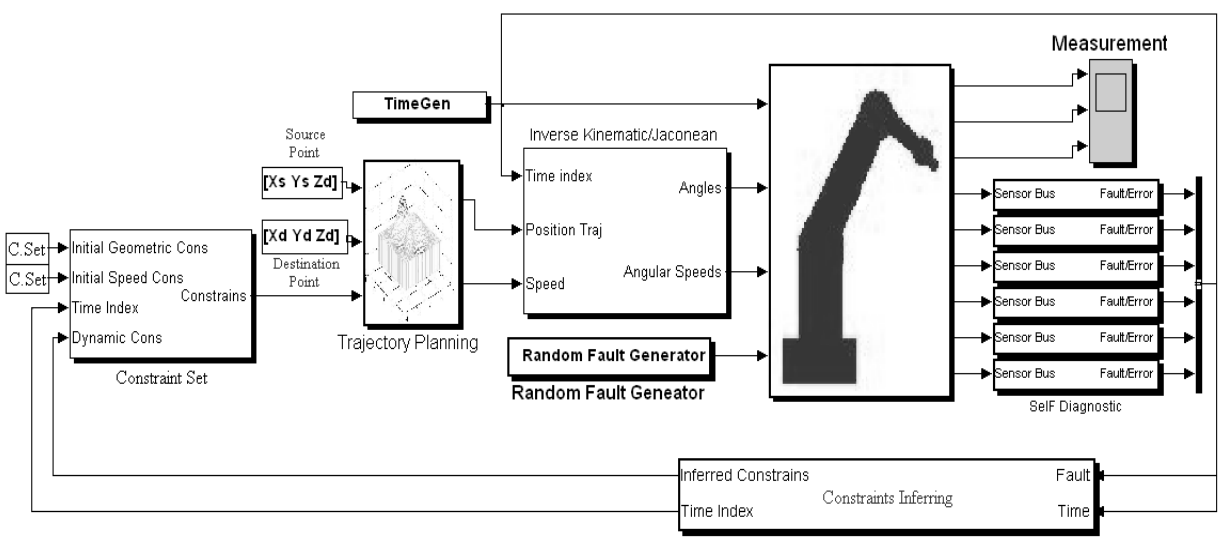

Figure 1- Simulink model for task completion for partially failed manipulator providing a point to point motion

$$Min \quad \left|\lambda V - \hat{V}\right| \qquad \text{Eq.(6)}$$

$$\left|\mu F - \hat{F}\right| = 0 \qquad \text{Eq.(7)}$$

where V is the desired velocity of the EEF and $\hat{V}$ is the velocity of the EEF after failure. and $0 \le \lambda \le 1$ is a scaling factor. Also F is the desired force of the EEF and $\hat{F}$ is the post failure EEF force. $0 \le \mu \le 1$ is a force scaling factor.

V. FAULT TOLERANT TRAJECTORY AND FORCE- A CASE STUDY

As it was mentioned earlier, the third case of the force tasks is the hardest problem as both trajectory and the force profile need to be maintained. To validate the strategy indicated in previous section a 3DOF planar manipulator is modelled and simulated using Matlab robotics toolbox[13]. The D-H parameters of the manipulator are indicated in Table-1. This manipulator is indicated in Figure 2, where it is providing a sample EEF trajectory.

TABLE 1

D-H PARAMETERS 3-DOF PLANAR MANIPULATORS

Link	$S_{i(m)}$	$D_{i\,(m)}$	α_i	θ_i
1	0	0.4	0	θ_1
2	0	0.3	0	θ_2
3	0	0.2	0	θ_3

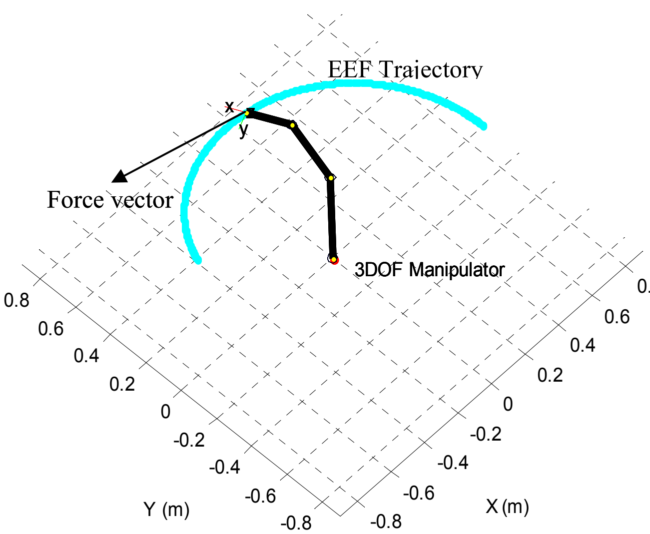

Figure 2- Trajectory and a sample force vector

For the given EEF trajectory in Figure 2 the joint angle profiles are indicated in Figure 3. It includes 3 joint profiles for the three joints. It is shown all joints are contributing to the motion of the EEF. The initial configuration is a zero $0^o C$ for all the joints and the final configuration is $90^o C, 60^o C, 80^o C$ for joint 1,2,and 3 respectively.

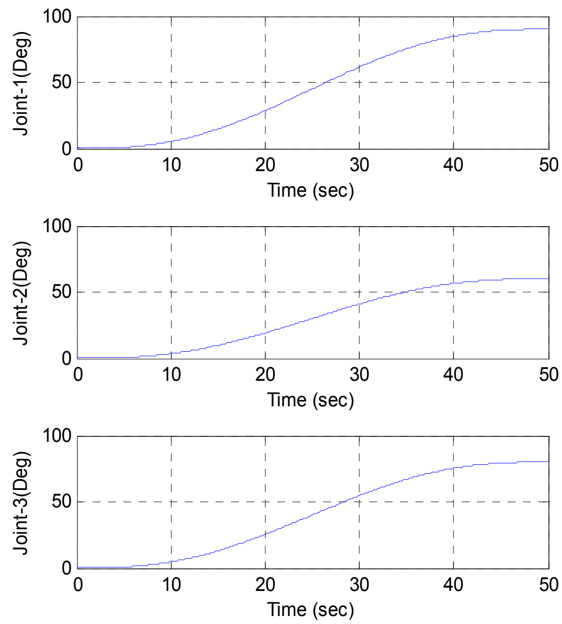

Figure 3- Joint velocity profiles

If the manipulator is providing a 40N force along its trajectory the joint torque profile to provide this force along the trajectory is indicated in Figure 4. The force is in the direction of the gradient of the EEF trajectory a sample force vector was indicated in Figure 2.

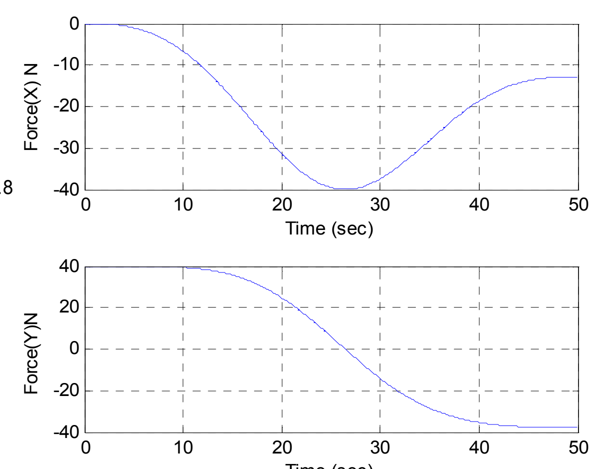

Figure 4- X and Y components of EEF force

Figure 5 indicates the joint torques to provide the force profiles in Figure 4. It indicates that all three joints are contributing to the force of the EEF.

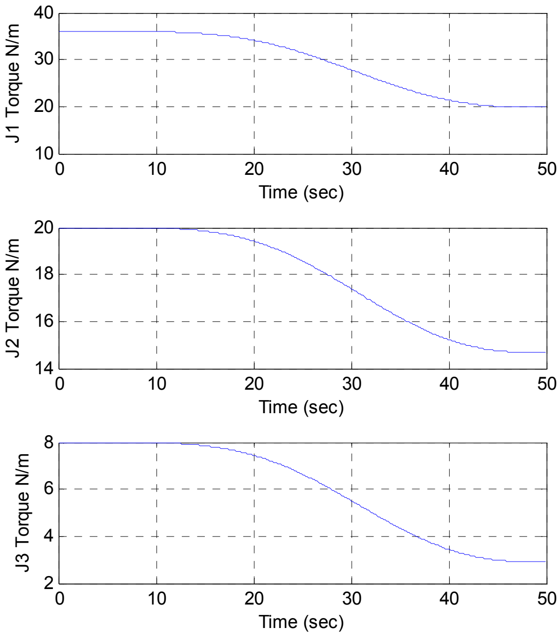

Figure 5- Joints' torque profiles for given force profile in Figure 4

The trajectory and the force profile both were provided by the 3DOF healthy manipulator as all the three joints are were contributing. If the second joint of this manipulator fails then the fault tolerant strategy should provide similar trajectory and similar force profile. The optimization problem in Eq.(6) and Eq.(7) has been applied and the results are obtained. In [12] the minimum velocity jump has been solved and in [14] the minimum force jump has been solved. Because the manipulator is a 3DOF and it is not singular at any given configuration for the desired velocity and force therefore both the trajectory and the force have been provided again. The new joint angle trajectories and joint torque profiles for the faulty manipulator are indicated in Figure 6 and Figure 7 respectively. In both figures the contribution of the second joint in the trajectory and the force of the EEF is zero showing the lock of the second joint. Also the contributions of the first and third joints have changed to tolerate the failure of the second joint. For example Figure 7 indicates that the healthy joints of the faulty manipulator are providing more torques in compare to their corresponding torque profiles in Figure 5.

Also by the torques in Figure 7, toleration of failure on the force of the EEF of the faulty manipulator has been observed.

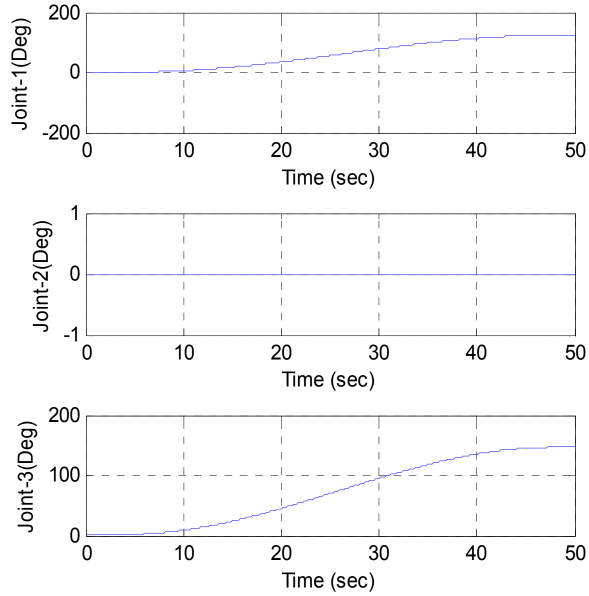

Figure 6- Joint angle trajectories when the second joint is failed

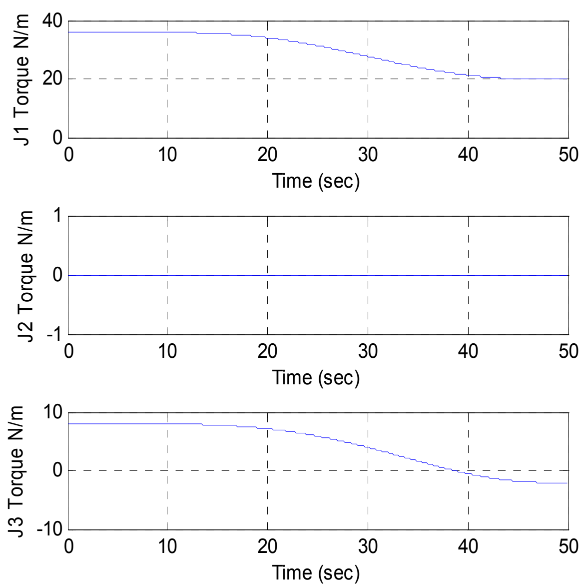

Figure 7- Joint torque trajectories when the second joint is failed

The final step is to show the new trajectory provided by the faulty manipulator. On this new trajectory the second joint must remain at its initial configuration and it should never along the trajectory. This trajectory and three samples of configuration of the manipulator are indicated in Figure 8, Figure 9 and Figure 10. All these figures are showing the tolerance of the second joint failure.

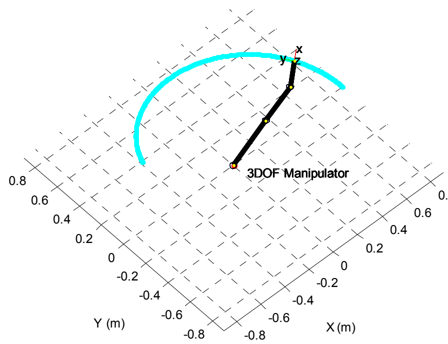

Figure 8- faulty manipulator at 15sec of its motion

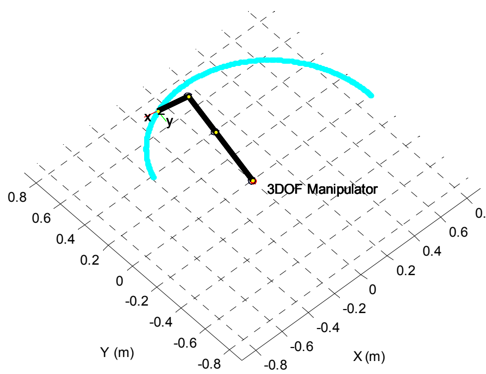

Figure 9- faulty manipulator at 30sec of its motion

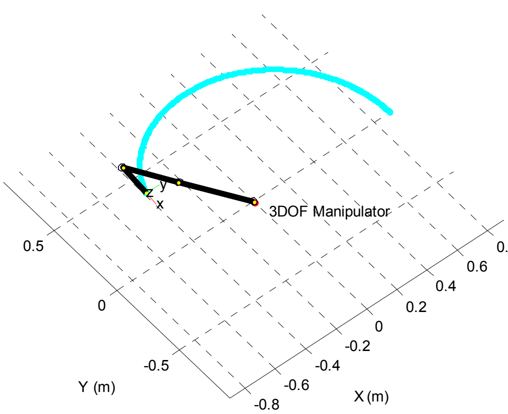

Figure 10- faulty manipulator at 50sec of its motion

VI. CONCLUSION

This paper aimed to put to gather the result of different aspects of the efforts for fault tolerance for partially failed manipulators. Then a sample problem for tolerating a locked joint failure of a 3DOF planar manipulator was achieved both for maintaining the trajectory and the force at the EEF of the manipulator.

To validate the proposed strategy for fault tolerance the resulted trajectory of a healthy manipulator and a faulty manipulators were provided, including the joint angle profiles, the EEF trajectory, the joint torques and the EEF force profiles. The comparison of the provided profiles indicates full fault recovery for the second joint locked failure of the 3DOF manipulator.

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