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Minimal Force Jump within Human and Assistive Robot Cooperation

Hamid Abdi, Member IEEE; Saeid Nahavandi, SMIEEE; Mehdi Tale Masouleh, Member ASME

Abstract: **When an assistant robotic manipulator cooperatively performs a task with a human and the task is required to be highly reliable, then fault tolerance is essential. .To achieve the fault tolerance force within the human robot cooperation, it is required to map the effects of the faulty joint of the robot into the manipulator's healthy joints' torque space and the human force. The objective is to optimally maintain the cooperative force within the human robot cooperation. This paper aims to analyze the fault tolerant force within the cooperation and two frameworks are proposed. Then they have been validated through a fault scenario. Finally, the minimum force jump which is the optimal fault tolerance has been achieved.**

Indexing terms: fault tolerant, robotic manipulators, human robot cooperation, actuator fault, reliability, least square minimization.

I. Introduction

Fault tolerant manipulators are essential where highly available robots are required such as robotic manipulators in hazardous environments, deep sea and outer space exploration [1]. The fault tolerance is critical when high dependability is required such as nuclear disposal and medical tele-surgery [2]. On the other hand the trend in the recent robotic research is to bring the robot to everyday life and human robot interaction (HRI), human robot cooperation (HRC) and their safety issues are challenging areas in robotics community. This work is in HRC and it aims to provide a fault tolerance force. Building on previous research work of the authors on fault tolerant force for a single robotic manipulator in [4] and cooperative manipulators in [17] the fault tolerance of the robotic manipulator within the HRC is addressed in this paper.

When a robotic manipulator assists a human for accomplishing a task such as tele-surgery or hazardous material handling; then it is more dependable if the cooperation is fault tolerance [3]. The problem is more interesting if the human force limitation and the optimality of the cooperation are considered.

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Hamid Abdi, Centre for Intelligent Systems Research (CISR), Deakin University, Waurn Ponds, VIC 3217, Australia, hamid.abdi@deakin.edu.au
Saeid Nahavandi, the director of CISR, Deakin University, Waurn Ponds, VIC 3217, Australia, saeid.nahavandi@deakin.edu.au
Mehdi Tale Masouleh, Université Laval, Département de génie mécanique, 1065 avenue de la Médecine, Québec, Canada, G1V 0A6, mehdi.tale-masouleh.1@ulaval.ca

The fault tolerant robotic manipulators should continue their task with minimum velocity and force jump on their task when a fault occurs into the joint/s of the robotic manipulator. If the manipulator is stationary while holding a payload then the force is only the matter of concern. The velocity jump for a single manipulators has been extensively studied by the authors in [5,18] and an algorithm to maintain the velocity of a faulty manipulator has been presented. For having a fault tolerant force it is essential to map the contribution of the locked joint for the force of the manipulator prior to the fault time to a proper command for the torque of the healthy joints and the human force. This problem is more complex when optimal operation and different strategies are desired.

The literature surrounding the fault tolerance within the HRC is studying different aspects of human robot interaction [6-7], human robot collaboration [8-9] and associated safety issues [10-11]. The fault tolerance within multi robot cooperation was discussed in [12] where software (ALLIANCE) has been developed for fault tolerant control of a team of mobile robots. In [13], through direct contact interaction a control strategy has been developed for HRC and two robots are directly supervised by a human to provide a fault tolerance force. Therefore the fault tolerance was achieved through redundancy in the robots. But from the literature review the fault tolerance within HRC specifically when they are applying a force has not been addressed. However, fault tolerant force control for parallel manipulator has been addressed [15] based on D'Alembert principle and equivalent force method. Cooperative manipulators are proposed for fault tolerant force control at their end-effector (EEF). The second manipulator is used to carry out the loss of the capacity of the first manipulator due to the fault for load handling in [14,17]. In this paper, the focus is on the fault tolerance of a single manipulator which cooperatively works with a human. The optimality of maintaining the force considering the manipulator and human limitations is presented.

The rest of the paper is organized as follows; at first the Jacobian for SLMs with some immobilized joints is introduced. Next the model of the joint torques and EEF force under faulty joint is used to calculate the force jump of the HRC. Then two cooperation strategies are proposed to maximally tolerate the force jump with in HRC. Finally the proposed frameworks are validated by a case study and their results are presented.

II. KINEMATICS OF REDUNDANT MANIPULATORS

A. Kinematics

The forward kinematics of a manipulator relates joint angles to the end-effector (EEF) position and orientation of the manipulators:

$$X = f(q) \tag{1}$$

$$q = [q_1 \quad q_2 \quad .... \quad q_n]^T \tag{2}$$

$$x = [x_1 \quad x_2 \quad ... \quad x_m]^T \tag{3}$$

The joint variables (2) define the configuration space and position/orientation variables (3) define the workspace of the manipulator. n is the configuration space dimension and the manipulator is *n-DOF*. m is the workspace dimension. The degree of kinematic redundancy (DOR) in non-singular configurations is *n-m*.

B. Jacobian matrix of Redundant Manipulator under Locked Joint Failures

Jacobian matrix (4) relates the EFF translational and orientational velocities to the joint velocities:

$$J = \left[\frac{\partial f}{\partial q}\right] \in R^{mn} \tag{4}$$

$$\dot{x} = J\dot{q} \tag{5}$$

Also J is used to analyze the force-torque relation via:

$$\tau = J^T F \text{ and } F = \left(J^T\right)^{\dagger} \tau \tag{6}$$

$$\left(J^T\right)^{\dagger} = \begin{cases} (JJ^T)^{-1}J & \text{if } J^T \text{ is not full rank} \\ J(J^TJ)^{-1} & \text{otherwise} \end{cases} \tag{7}$$

If J_k in (8) is the k^{th} columns of $\left(J^T\right)^{\dagger}$

$$\left(J^T\right)^{\dagger} = [J_1 \quad J_2 \quad . \quad . \quad J_{k-1} \quad J_k \quad J_{k+1} \quad . \quad . \quad J_n]_{mn} \tag{8}$$

Each column indicates the contribution of the corresponding joint torque in the force of the EEF in Eq.(6). When manipulator has a fault in the k^{th} joint, this joint does not contribute into EFF force. Therefore the Jacobian of the manipulator under the faulty joint fault can be introduced by replacing a zero vector in the k^{th} column of (8) this is called reduced Pseudo Inverse Jacobian matrix:

$${}^k\left(J^T\right)^{\dagger} = [J_1 \quad J_2 \quad . \quad . \quad J_{k-1} \quad 0 \quad J_{k+1} \quad . \quad J_n \quad] \tag{9}$$

and we have ${}^kF = {}^k\left(J^T\right)^{\dagger}\,{}^k\tau$ and

$${}^k\left(J^T\right)^{\dagger} = [J_1 \quad J_2 \quad . \quad . \quad J_{k-1} \quad J_{k+1} \quad . \quad . \quad J_n \quad] \tag{10}$$

$${}^k\tau = [\tau_1 \quad \tau_2 \quad . \quad . \quad \tau_{k-1} \quad \tau_{k+1} \quad . \quad . \quad \tau_n \quad]^T \tag{11}$$

For one possible fault there will be n reduced Jacobian matrices indicated by:

$$\left\{{}^1\left(J^T\right)^{\dagger}, {}^2\left(J^T\right)^{\dagger} ..., {}^n\left(J^T\right)^{\dagger}\right\} \tag{12}$$

With this approach; if the manipulator has f faults, then the reduced Jacobian matrices are indicated with permutation of f zero vectors in the original Jacobian matrix. In general, if there are f (*f=1..n*) then there are $\binom{n}{f} = \frac{n!}{f!(n-f)!}$ different possible reduced Jacobian matrices. For two faults there are $\frac{n(n-1)}{2}$ reduced Jacobian matrices as:

$$\left\{{}^{k,i}\left(J^T\right)^{\dagger} = [J_1 \quad . \quad J_{k-1} \quad 0 \quad J_{k+1} \quad ... \quad J_{i-1} \quad 0 \quad J_{i+1} \quad .. \quad J_n]\right\} \tag{13}$$

where $k, i = 1..n, i > k$.

These matrices are used to rewrite Eq. (6) as:

$$F = {}^{k,i}\left(J^T\right)^{\dagger}\,{}^{k,i}\tau \tag{14}$$

$$\left\{{}^{k,i}\left(J^T\right)^{\dagger} = [J_1 \quad . \quad J_{k-1} \quad J_{k+1} \quad ... \quad J_{i-1} \quad J_{i+1} \quad .. \quad J_n]\right\} \tag{15}$$

$$\left\{{}^{k,i}\tau = [\tau_1 \quad . \quad \tau_{k-1} \quad \tau_{k+1} \quad ... \quad \tau_{i-1} \quad \tau_{i+1} \quad .. \quad \tau_n]^T\right\} \tag{16}$$

III. FORCE JUMP DUE TO JOINT FAULT

A. EEF Force and Joint Torque for HRC

For a cooperative human and serial manipulator, and in a given pose of the manipulator, applying a force for the task is divided into the human force and the manipulator force:

$$F = {}_mF + {}_hF \tag{17}$$

The force of the manipulator is related to the joint torques by the transpose of the Jacobian matrix of the manipulator:

$${}_mF = \left({}_mJ^T\right)^{\dagger}\,{}_m\tau \tag{18}$$

where:

F : force for the task

${}_mF$: force at the EEF of the manipulator

${}_hF$: force of the human

${}_m\tau$: torques of the manipulators

The dynamic equation of the manipulator is:

$${}_mM({}_mq)_m\ddot{q} + {}_mV({}_mq, {}_m\dot{q})_m\dot{q} + {}_mG({}_mq) = {}_m\tau_d \tag{19}$$

${}_mM({}_mq)$: mass matrix

$_mV(_mq,_m\dot{q})$: Coriolis and centrifugal term

$_mG(_mq)$: gravity term

$_m\tau_d$: torque to provide the desired motion profile

If the manipulator is required to provide a force at its EEF or a force is applied to the EEF, to provide the required F at the EEF of each manipulator the torque is indicated by Eq.(18) is required to be added into Eq.(19) and results in:

$$_mM(_mq)_m\ddot{q}+_mV(_mq,_m\dot{q})_m\dot{q}+_mG(_mq)=_m\tau_d+_mJ^T{}_mF \qquad (20)$$

If $_m\tau$ is the joint torques to provide the $_mF$, then for non redundant manipulators the force is obtained by $_mF=\left(_mJ^T\right)^{-1}{}_m\tau$, but for the redundant manipulators the force is calculated via generalized inverse as:

$$_mF=\left(_mJ^T\right)^{\dagger}{}_m\tau+\left(I-\left(_mJ^T\right)^{\dagger}{}_mJ^T\right)_mz \qquad (21)$$

$\left(_mJ^T\right)^{\dagger}$ is the pseudo inverse (Penrose-Moore inverse) of the $_mJ^T$ as was defined by Eq.(7) and following:

$$\left\{I-\left(_mJ^T\right)^{\dagger}\left(_mJ^T\right)\right\} \qquad (22)$$

is the projection matrix into the null space of $\left(_mJ^T\right)^{\dagger}$.

B. Modeling of locked joint failure trough matrix perturbation

If the k^{th} joint of the manipulator is locked then the k^{th} reduced Jacobian is ${}^k_1J$. From perturbation model [5], if this fault is modeled by variation in the inverse Jacobian matrix then force at the EEF and joint torque equation is obtained from Eq.(18) as:

$$_mF+_m\Delta F=\left(\left(_mJ^T\right)^{\dagger}+\Delta\left(_mJ^T\right)^{\dagger}\right)\left(_m\tau+_m\Delta\tau\right) \qquad (23)$$

where $_m\Delta\tau$ is the change into the torques at fault time, $\Delta\left(_mJ^T\right)^{\dagger}$ Jacobian matrix perturbation due to fault and $_m\Delta F$ is the force jump at EEF of the first manipulator before compensation.

Generally, Eq.(23) results to a force jump at the EEF. For fault tolerating the force jump, it is required to find a new joint's torque to minimize the force jump in the HRC. The required change into the joint's torques is assumed as $_mU$ therefore:

$$_mF+_m\Delta\hat{F}=\left(\left(_mJ^T\right)^{\dagger}+\Delta\left(_mJ^T\right)^{\dagger}\right)\left(_m\tau+_m\Delta\tau+_mU\right) \qquad (24)$$

where:

$_mU$: compensating Joint torque for the manipulator

$_m\Delta\hat{F}$: force jump at EEF of the manipulator after compensation

If the fault occurs into the k^{th} joint, then the perturbation model is obtained by:

$$_mF+_m\Delta\hat{F}={}^k\left(_mJ^T\right)^{\dagger}\left(_m\tau+_m\Delta\tau+_mU\right) \qquad (25)$$

where

$$\Delta\left(_mJ^T\right)^{\dagger}=\begin{bmatrix}0 & \dots & -_mJ_k & \dots & 0\end{bmatrix} \qquad (26)$$

$$\left(_mJ^T\right)^{\dagger}+\Delta\left(_mJ^T\right)^{\dagger}={}^k\left(_mJ^T\right)^{\dagger} \qquad (27)$$

${}^k_mU$: compensating Joint torque for the manipulator when the k^{th} joint is locked

If the human force after the failure is changed by $_h\Delta F$ then the total force after the failure is $\tilde{F}$

$$\tilde{F}=_mF+_m\Delta\hat{F}+_hF+_h\Delta F \qquad (28)$$

Substitution of Eq.(25) results in:

$$\tilde{F}={}^k\left(_mJ^T\right)^{\dagger}\left(_m\tau+_m\Delta\tau+_mU\right)+_hF+_h\Delta F \qquad (29)$$

For fault tolerant force it requires to have $\tilde{F}=F$. But if compensation does not fully recover the force, then the force jump is obtained by $\Delta\hat{F}=\tilde{F}-F$ which is:

$$\Delta\hat{F}=_m\Delta\hat{F}+_h\Delta F=\left(\left(_mJ^T\right)^{\dagger}+\Delta\left(_mJ^T\right)^{\dagger}\right)\left(_m\tau+_m\Delta\tau+_mU\right) -\left(_mJ^T\right)^{\dagger}{}_m\tau+_h\Delta F \qquad (30)$$

$$\Delta\hat{F}={}^k\left(_mJ^T\right)^{\dagger}{}_m\Delta\tau+{}^k\left(_mJ^T\right)^{\dagger}{}_mU+\Delta\left(_mJ^T\right)^{\dagger}{}_m\tau+_h\Delta F \qquad (31)$$

Simply it is known that $\left(\left(_mJ^T\right)^{\dagger}+\Delta\left(_mJ^T\right)^{\dagger}\right)_m\Delta\tau=0$ because $\left(\left(_mJ^T\right)^{\dagger}+\Delta\left(_mJ^T\right)^{\dagger}\right)$ has a zero vector on its k^{th} column and $_m\Delta\tau$ is a zero vector except on its k^{th} raw.

If it is required to have minimum force jump then the minimization problem is introduced as:

$$\underset{_mU,_h\Delta F}{Min}\ \left\|\Delta\hat{F}\right\|^2 \qquad (32)$$

C. Minimization of force jump

Two fault tolerant strategies are presented for the cooperation. The minimization of force jump is illustrated in following. In the first strategy the manipulator is the required to optimally tolerate the force, and the human contributes if the manipulator cannot tolerate the force. In the second strategy the human is responsible for tolerating the fault but the manipulator contributes if it is out of human force range.

Strategy I: the manipulator maximally compensates the force jump due to the fault and the remainder of force jump is compensated by the human. To have the framework, let first assume the human does not change the force, therefore ${}_h\Delta F = 0$. Based on Eq.(33) a minimum force jump is achieved when $\Delta\hat{F}$ in following is minimized via:

$$\Delta\hat{F} = {}^k\left({}_mJ^T\right)^{\dagger}\,{}_mU + \Delta\left({}_mJ^T\right)^{\dagger}\,{}_m\tau \tag{33}$$

Using least square technique, the optimal manipulator joint torques to minimize the force jump is indicated in:

$$ {}_mU = -\left({}^k\left({}_mJ^T\right)^{\dagger}\right)^{\dagger}\left\{\Delta\left({}_mJ^T\right)^{\dagger}\,{}_m\tau\right\} \tag{34}$$

If under Eq.(34) there still exists a force jump then that force jump is $\Delta\hat{F}_{\min}$ which is the minimum force jump if only manipulator tries to tolerate the fault:

$$\Delta\hat{F}_{\min} = \left(I - {}^k\left({}_mJ^T\right)^{\dagger}\left({}^k\left({}_mJ^T\right)^{\dagger}\right)^{\dagger}\right)\left\{\Delta\left({}_mJ^T\right)^{\dagger}\,{}_m\tau\right\} \tag{35}$$

where I is a identity matrix, then this force jump is required to be compensated by the human. Therefore the required change into the human force is:

$$ {}_h\Delta F = \left(I - {}^k\left({}_mJ^T\right)^{\dagger}\left({}^k\left({}_mJ^T\right)^{\dagger}\right)^{\dagger}\right)\left\{\Delta\left({}_mJ^T\right)^{\dagger}\,{}_m\tau\right\} \tag{36}$$

Physically Eq.(36) means that the human is only required to apply the projection of the manipulator force jump into the null space of the reduced inverse Jacobian of the manipulator. If the human force is limited to the ${}_h\Delta F_{\max}$ then the unavoidable force jump is ${}_h\Delta F - {}_h\Delta F_{\max}$ and it is indicated by:

$$\Delta F_f = \left(I - {}^k\left({}_mJ^T\right)^{\dagger}\left({}^k\left({}_mJ^T\right)^{\dagger}\right)^{\dagger}\right)\left\{\Delta\left({}_mJ^T\right)^{\dagger}\,{}_m\tau\right\} - {}_h\Delta F_{\max} \tag{37}$$

ΔF_f is final unavoidable force jump

The final force jump will be zero if the faulty reduced inverse Jacobian remains full rank (this is similar to say that the projection into null space in Eq.(36) is zero) or the projection is in the limit of the human force.

Strategy II: the fault in the manipulator has to be maximally resolved by the human. In this case, the human tries to optimally tolerating the force while a minimum toleration is asked from the manipulator. This can be justified, when the availability of the robot is important and the human tries to prevent any subsequent failure in the manipulator. But fault tolerance has more priority therefore the manipulator contributes iff human cannot tolerate the force. Assuming the human maximally compensates the fault therefore one can initially assume that the manipulator torque change is zero (${}^k_mU = 0$). Then for a zero force jump in the change into the human force is obtained as:

$$\Delta\hat{F} = \Delta\left({}_mJ^T\right)^{\dagger}\,{}_m\tau + {}_h\Delta F \tag{38}$$

$$ {}_h\Delta F = -\left\{\Delta\left({}_mJ^T\right)^{\dagger}\,{}_m\tau\right\} \tag{39}$$

But if the maximum compensation force of the human is ${}_h\Delta F_{\max}$, then ${}_h\Delta F - {}_h\Delta F_{\max}$ is:

$$\Delta\hat{F} = {}_h\Delta F - {}_h\Delta F_{\max} = -\left\{\Delta\left({}_mJ^T\right)^{\dagger}\,{}_m\tau\right\} - {}_h\Delta F_{\max} \tag{40}$$

which is required to be optimally resolved by the manipulator. And as the result the optimum torque to recover this force is:

$$ {}_mU = -\left({}^k\left({}_mJ^T\right)^{\dagger}\right)^{\dagger}\left\{\Delta\left({}_mJ^T\right)^{\dagger}\,{}_m\tau - {}_h\Delta F_{\max}\right\} \tag{41}$$

And the final unavoidable force jump is :

$$\Delta F_f = \left(I - {}^k\left({}_mJ^T\right)^{\dagger}\left({}^k\left({}_mJ^T\right)^{\dagger}\right)^{\dagger}\right)\left(\Delta\left({}_mJ^T\right)^{\dagger}\,{}_m\tau + {}_h\Delta F_{\max}\right) \tag{42}$$

The final force jump, is the projection of the force jump after human compensation in Eq.(40) into null space of the reduced inverse Jacobian matrix.

These frameworks are general as the faulty joint is assumed as an arbitrary joint (k^{th} joint, $k=1..n$).

To validate the frameworks proposed in the previous section; A case studies are presented as following. The aim is to optimally maintain a required force for a force task within HRC when a fault occurs into the manipulator joint.

IV. Case Study I

A. Case study parameters

Table 1 indicates D-H parameter of a 3DOF planar manipulator. Table 2 indicates the parameters of the manipulator prior to the fault time. The manipulator configuration is illustrated in Fig.1.
It is assumed that human and the manipulators are cooperatively providing a planar force of $F = [50_N \quad 80_N \quad 0_N]^T$ and human force is limited to $F_h = [20_N \quad 20_N \quad 0_N]^T$. Then a fault is assumed to occur into the 2nd joint of the manipulator. The human force prior to the fault time is ${}_hF = [5_N \quad 10_N \quad 0_N]^T$ and it is indicated in Fig.1 by a doted arrow.

TABLE 1

D-H PARAMETERS OF MODELED A 3DOF PLANAR MANIPULATOR

Joint No	$S_{i(m)}$	$D_{i\,(m)}$	$\alpha_{i(RAD)}$	θ_i
1	0.05	0.50	0	θ_1
2	0.05	0.40	0	θ_2
3	0.05	0.30	0	θ_3

TABLE 2

CONFIGURATION AND PARAMETERS OF THE MANIPULATOR AT FAULT TIME

Joint No	Angle Q deg	Torque τ (N.m)	Force at the EEF of the manipulator
1	25	13.03	$_mF = \begin{bmatrix} 45_N \\ 70_N \\ 0_N \end{bmatrix}$
2	90	43.59	
3	80	21.00	

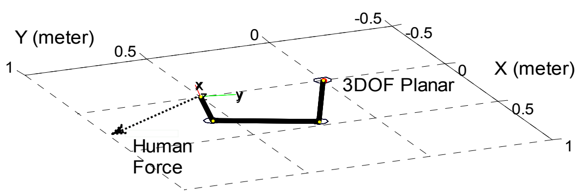

Fig. 1. The manipulator configuration and human force. The human force is indicated by doted arrow.

B. Validation of cooperation strategies

Strategy I: The manipulator maximally tries to resolve the fault. Using the framework provided in Eq.(34) and Eq.(36); the result is indicated in Table 3. It is clear that the fault can be resolved by the manipulator as two DOFs have remained.

TABLE 3

HUMAN AND MANIPULATOR FORCE AND TORQUE WHEN THE MANIPULATOR MAXIMALLY WORKS TO RESOLVE THE FAULT

Joint No	Joint torque after compensation	Force jump at fault time	Manipulator force after compensatio n	Human Force	Force Jump
1	48.74	$\begin{bmatrix} 32.11_N \\ 55.17_N \\ 0_N \end{bmatrix}$	$\begin{bmatrix} 45_N \\ 70_N \\ 0_N \end{bmatrix}$	$\begin{bmatrix} 5_N \\ 10_N \\ 0_N \end{bmatrix}$	$\begin{bmatrix} 0_N \\ 0_N \\ 0_N \end{bmatrix}$
2	Locked				
3	89.32				

Strategy II: The human maximally tries to resolve the fault by considering his force limit. And the rest of the force has to be compensated by the manipulator. The result of this strategy bases on Eq.(39)-Eq.(43) is indicated in Table.4. Again the fault is resolved by the manipulator as it has 2DOF remained.

TABLE 4

HUMAN AND MANIPULATOR FORCE AND TORQUE WHEN THE MANIPULATOR MAXIMALLY WORKS TO RESOLVE THE FAULT

Joint No	Joint torque after compensation	Force jump at fault time	Manipulator force after compensation	Human Force	Force Jump
1	34.89	$\begin{bmatrix} 32.11_N \\ 55.17_N \\ 0_N \end{bmatrix}$	$\begin{bmatrix} 30_N \\ 60_N \\ 0_N \end{bmatrix}$	$\begin{bmatrix} 20_N \\ 20_N \\ 0_N \end{bmatrix}$	$\begin{bmatrix} 0_N \\ 0_N \\ 0_N \end{bmatrix}$
2	Locked				
3	71.26				

V. CASE STUDY II

In this case study a Puma 560 manipulators is used within a HRC structure. The problem is to maintain a force as a given point. The manipulator has been modeled in Matlab Robotics Toolbox [16].

A. Case study parameters

Table 5 and Table 6 indicate D-H parameter prior to fault time and the manipulator configuration parameters prior to fault time. The manipulator configuration is indicated in Fig.2.

TABLE 5

D-H PARAMETERS OF MODELED PUMA560 MANIPULATOR

Joint No	$S_{i(m)}$	$D_{i\,(m)}$	$\alpha_{i(RAD)}$	θ_i
1	0	0	1.57	θ_1
2	0	0.4318	0	θ_2
3	0.15	0.0203	-1.57	θ_3
4	0.43	0	1.57	θ_4
5	0	0	-1.57	θ_5
6	0	0	0	θ_6

It is assumed that human and the manipulators are cooperatively providing $F = [50_N \quad 80_N \quad 10_N]^T$ at the EEF. The force of the manipulator is provided by only the arm joints of the manipulator.

TABLE 6

CONFIGURATION AND PARAMETERS OF THE MANIPULATOR AT FAULT TIME

Joint No	Angle Q deg	Torque τ n.m	Human force prior to fault	Manipulator force prior to fault
1	25	-11.20		
2	60	-13.83	$\begin{bmatrix} 5_N \\ 10_N \\ 5_N \end{bmatrix}$	$\begin{bmatrix} 45_N \\ 70_N \\ 5_N \end{bmatrix}$
3	10	-19.33		
4	0	0		
5	0	0		
6	0	0		

Then a fault is assumed to occur into the 2nd joint of the manipulator. The human force is $_hF = [5_N \quad 10_N \quad 5_N]^T$ and it is indicated in Fig.1 also it is limited to $[20_N \quad 20_N \quad 20_N]^T$.

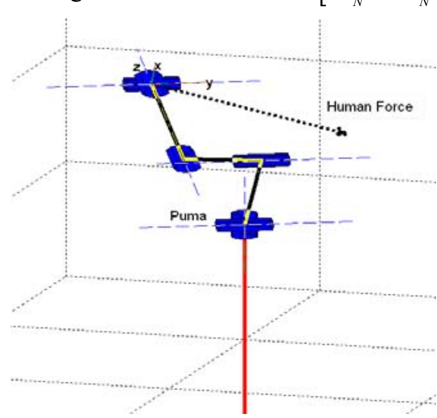

Fig. 2. The manipulator configuration and human force The human force is indicated by doted arrow.

B. Validation of cooperation strategies

Strategy I: The manipulator maximally tries to resolve the fault. Using the framework provided in Eq.(34) and Eq.(36); the result is indicated in Table 7. It is clear that the fault can be resolved by the manipulator as two DOFs have remained.

TABLE 7

HUMAN AND MANIPULATOR FORCE AND TORQUE WHEN THE MANIPULATOR MAXIMALLY WORKS TO RESOLVE THE FAULT

Joint No	Joint torque after compensation	Force jump at fault time	Manipulator force after compensation	Human Force	Force Jump
1	-14.64				
2	Locked				
3	-12.41	$\begin{bmatrix} -1.52_N \\ 24.44_N \\ -32.25_N \end{bmatrix}$	$\begin{bmatrix} 29.86_N \\ 70.00_N \\ 23.91_N \end{bmatrix}$	$\begin{bmatrix} 20_N \\ 10_N \\ -13.91_N \end{bmatrix}$	$\begin{bmatrix} 0.14_N \\ 0_N \\ 0_N \end{bmatrix}$
4	0				
5	0				
6	0				

Strategy II: The human maximally tries to resolve the fault by considering his force limit. The rest of the force has to be compensated by the manipulator. The result of the strategy bases on Eq.(39)-Eq.(43) is indicated in Table 8.

TABLE 8

HUMAN AND MANIPULATOR FORCE AND TORQUE WHEN THE MANIPULATOR MAXIMALLY WORKS TO RESOLVE THE FAULT

Joint No	Joint torque after compensation	Force jump at fault time	Manipulator forc after compensatio	Human Force	Force Jump
1	-18.61				
2	Locked				
3	-8.98	$\begin{bmatrix} -1.52_N \\ 24.44_N \\ -32.25_N \end{bmatrix}$	$\begin{bmatrix} 21.87_N \\ 97.44_N \\ 17.30_N \end{bmatrix}$	$\begin{bmatrix} 6.52_N \\ -14.44_N \\ -20_N \end{bmatrix}$	$\begin{bmatrix} 21.87_N \\ 0_N \\ -27.30_N \end{bmatrix}$
4	0				
5	0				
6	0				

C. Discussion

The fault scenarios illustrated the proposed frameworks for fault tolerant force within HRC. In the second case study; hence the manipulator force was provided by the arm joints of the PUMA560, therefore failure of one of them resulted to a non full rank Jacobian matrix and considering the limitation of the human force, a force jump has occurred in both strategies.

VI. CONCLUSION

Fault tolerant force through HRC was addressed. The fault tolerance was optimally achieved under two strategies. Then a framework for optimal cooperation for each strategy was mathematically obtained. The minimum force jump was calculated by considering the reduced manipulator inverse Jacobian rank and the human force limit. Two case studies were used to validate the framework and via them an optimal human force and optimal manipulator healthy joints' torques were calculated and the minimum force jump for their cooperation has been achieved.

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