DISTRIBUTED COOPERATIVE SYNCHRONIZATION CONTROL OF 2 ARTICULATED ROBOTS FOR INDUSTRY 4.0 APPLICATION

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ABSTRACT: A distributed cooperative synchronization control involving two robotic arms were designed and developed. Two slave robot arms were connected over a network allowing them to exchange control signal and angular position feedback data whilst performing a challenging cooperative task. The master arm unit provides the desired trajectory to which the slave unit will follow. Using the concept of Hardware-in-the-loop (HIL), the cost effective Arduino Mega 2560 microcontroller hardware can be utilized within the eco-system of MATLAB® Simulink environment due to the availability of Simulink Support Package for Arduino microcontroller. MATLAB® computation ablity allows matrix multiplication to be performed efficiently. As it is distributed system, 2 Arduino Mega 2560 microcontroller board are used as the distinctive 'brain' for each respective robotic arm. To achieve excellent synchronization, cooperative phase lead compensated control is used to let the robot arms to move in accurate motion in the same manner between the interaction of master feedback unit and both slave robot arms as the position error is reduced. The controlled system performance was measured by using Integral Absolute Error (IAE) to observe the synchronization accuracy. The outcome of this project was expected to bring an immense impact to beneficial use in production and manufacturing, in particular, in the age of Industrial Revolution 4.0.

KEYWORDS: *Cooperative Control; Distributed Control System; Frequency Response Modelling; Multiple Robot Arms; Phase-lead Compensator Control*

1.0 INTRODUCTION

Cooperative robotics has been fast growing in lots of industrial fields around the world. The implementation of cooperative attracted growing in research network which allows new ways to do variety of application (Jaisumroum, Chotiprayanakul, & Limnararat, 2017). However, a single robot arm is not as superior as the two or more robot arms when a cooperative task is to be commissioned. Dual-arm robots have added advantages such as strong cooperative ability and high reliability in comparison to singl robot arm (Bai, Luo, Liu, & Jiang, 2015). A cooperative task such as parts assembly require one robot arm to hold the part in place whilst the other robot arm will be functioning to secure or fix the other parts in place (Wagner, Hess, Reitlershöfer & Franke, , 2016). However, therecomes the problem of controlling the two robot arms for a cooperative task. There are at times, the motion of the two robot arms need to be synchronized. This requires a cooperative control scheme which able to control both arms synchronously in the pursuit to achieve a cooperative task (Khan, Bendoukha & Mahyuddin, 2017). The two articulated robot arms can be connected over a network by which control signals of the robot will be shared across (Mahyuddin & Herrmann, 2013). The shared information about each robot was exchanged among them, producing a synchronization control signal for cooperative control task.

A group of robots can be comanded to carry out task that are impossible for a single robot

(Schwung, Csaplar, Schwung, & Ding, 2017). Mean-time, the changes from isolated robot operation to cooperative mul-tiple robot make the complexity of the applied industrial robot station and the smart inter-connectivity grew to become harder (Zitouni & Maamri, 2016). In industry, cooperative robot system can offer high productivity, minimize labor cost, and completed risky or poisonous substances (Helwa & Schoellig, 2017). As it is very risky for human to do task in this kind of environment as it can give side effect to the health of even can cause death.

This paper presents the design and the development cooperatively-controlled two robotic arms (MENTOR robots) performing a delicate cooperative task. Each robot is deemed as an agent robot working together with another agent robot to perform a cooperative task which single robot cannot do. The developed project is to illustrate the efficacy of a cooperative control algorithm to perform a task which requires cooperation, i.e., involving exchanging information across between two agent robots. Despite of the hardware constraint of the MENTOR robot, in particular, the absence of torque sensor to read the torque feedback, cooperative control has been successfully implemented on the MENTOR robots. Decoupled discrete phase-lead controller was designed for each link to follow the Master unit whilst utilizing the synchronization error exchanged between the two MENTOR robots.

The contribution embarked in this research can be summarized as follow:

1. The design of discrete phase-lead controller at joint-space in cooperative setup.
2. The use of Matlab Simulink and the supported Arduino toolbox as a Rapid-Control Prototyping tool.
3. Hardware validation on a industrial articulated robotic arm, commissioning to perform a delicate cooperative tasks, i.e., balancing a glass of water on a tray cooperatively hold by both robotic arms.

2.0 System Description

As shown in Figure 1, two Mentor industrial articulated robot arms were commissioned to work in achieving a delicate cooperative task. Each MENTOR robot is capable of performing pick-and-place operation within its work envelope. In this project, however, they were required to share the task objective, i.e. holding a tray together and moving it up and down whilst keeping the balance to avoid the glass of water on the tray from spilling over.

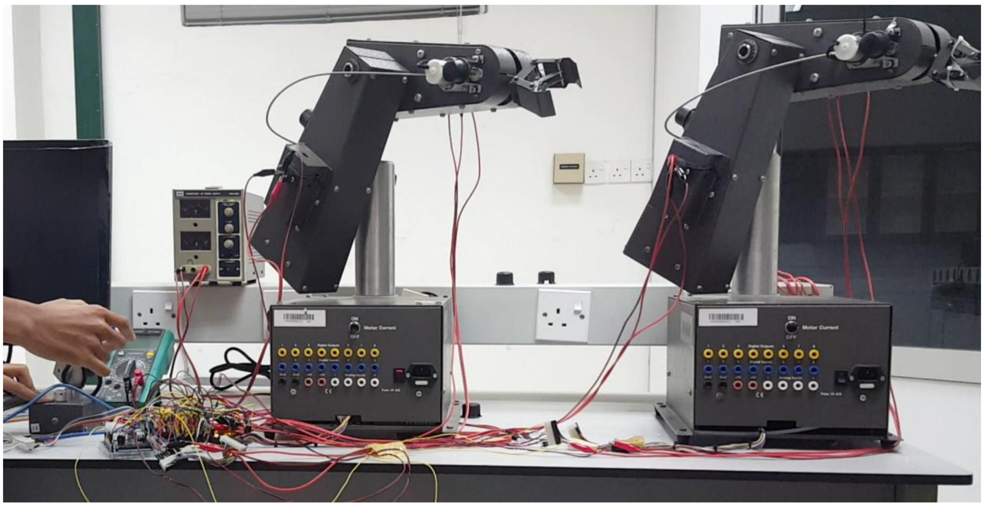


Fig 1. Two articulated industrial robot arms setup

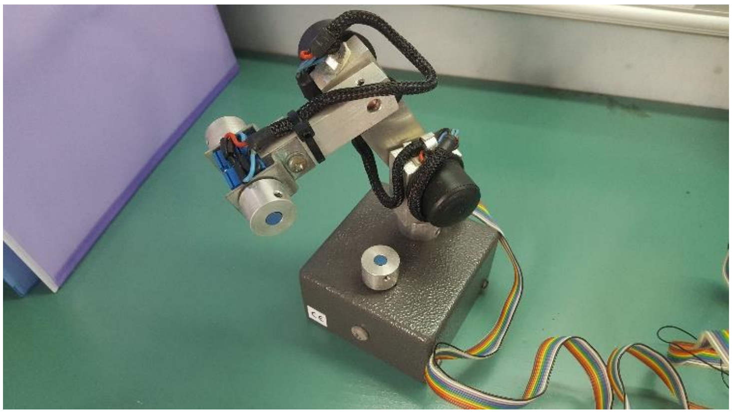


Fig 2. A Master unit to which the MENTOR robot will follow as the desired motion to command.

Figure 2 shows a smaller dedicated Master unit (comprised of high resolution potentiometer at each passive joint) which resembles that of the bigger articulated robotic arm without the DC motor. The Master unit serves as the 'leader' unit which provides the desired trajectory for each joint to which robotic arm will follow.

2.1 Kinematic Representation

Figure 3 represents the kinematic configuration of each MENTOR robotic arm. The respective Denavit-Hartenberg parameters were derived from the diagram, creating a set of relevant D-H parameters as tabulated in Table 1.

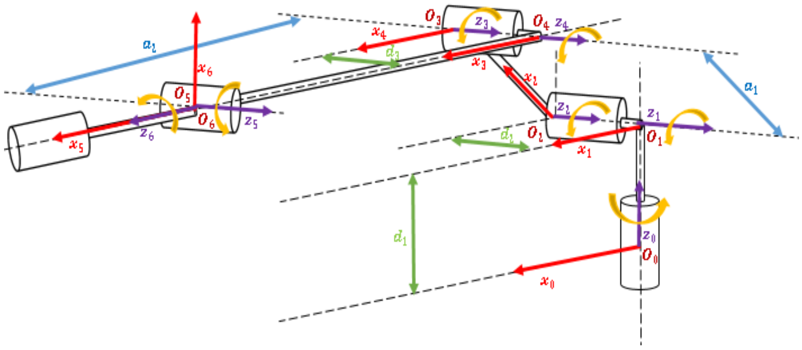


Fig 3 A diagram showing the kinematic representation of each articulated robotic arm

Table 1: D-H parameter for Master and Slave robotic arms considering all joints

Joint i	α_i	a_i	d_i	θ_i
1	-90	0	d_1	θ_1
2	0	0	d_2	θ_2
3	0	a_1	0	θ_3
4	0	0	d_3	θ_4
5	0	a_2	0	θ_5
6	-90	0	0	θ_6

The respective derived D-H parameters were utilized in the analysis to determine whether the end-effector (the gripper) of the Mentor robot arm was commanded correctly in following the trajectory provided by the Master unit.

2.2 Software and Hardware development of Cooperative Control System

MATLAB® Support Package for Arduino® Hardware as shown in Figure 4 allows MATLAB to control Arduino outputs and inputs. It will make interactively communication between Arduino and MATLAB. This add-ons enables MATLAB to acquire analog and digital sensor data from the Arduino Board and other functions [18].

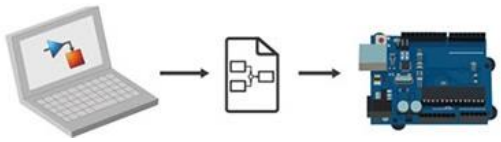


Fig. 4 Simulink Support package from MATLAB® was utilized as part of Rapid Control Prototyping method in Cooperative Control design and synthesis

Simulink support package for Arduino was installed in the MATLAB® environment to allow Simulink-based Cooperative Phase-Lead Control algorithm (shown in Figure 5) be compiled and downloaded into the Arduino microcontroller.

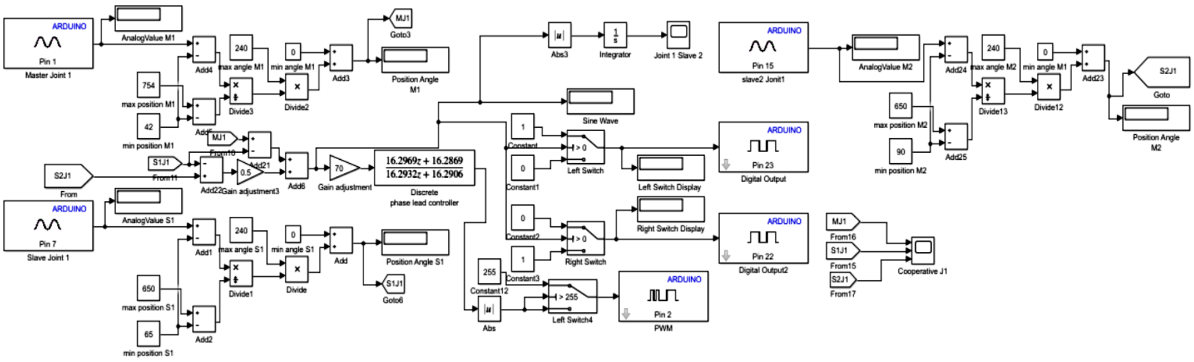


Fig. 5 A screenshot of the Simulink-based Cooperative Phase-Lead Control Design and its corresponding Arduino Support package.

The Hardware-in-the-Loop (HIL) concept approach as depicted in Figure 5 was employed which allows full utilization of the MATLAB®'s efficient software capability in matrix multiplication but at the same time, using the cost-effective hardware capability of the Arduino microcontroller in this project. The MATLAB® was able to compute the output of the designed phase-lead controller at the level of floating-point (instead of fixed-point). Such methodology allows seamless access to the input and output ports of the microcontroller, transmitting the control signals and reading the angular position sensors of the MENTOR robot arms.

3.0 Decoupled Phase-Lead Controller Design

In this project, due to the unavailability of torque sensors (or alternatively, the current feedback from the motor) to measure net torque at each joint, computed torque control design would not be feasible. Therefore, it is assumed that the motion commanded by the Master unit allows the dynamics for each robot link exert minimal impact on its connected link thereby reducing the coupling effect. Consequently, due to this decoupled assumption being drawn, separate discrete phase-lead control design can be designed for each actuator. To allow realistic compensation for the practical MENTOR robot arm, the dynamic model of individual link of the robot arm need to be found.

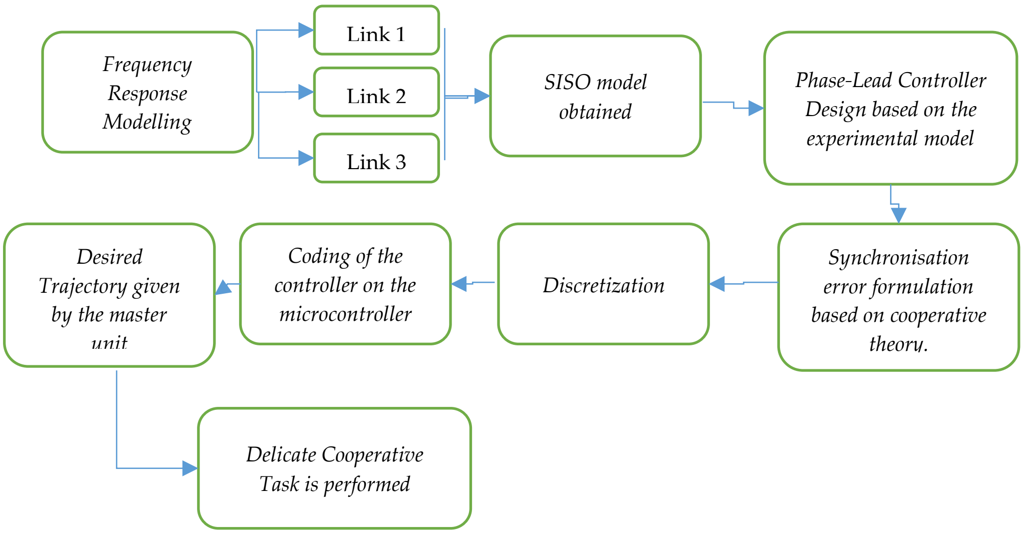


Fig 6. Cooperative Control Design methodology

3.1 Experimental Frequency response modelling

A set of experimental frequency response modelling was implemented to obtain the single-input-single-output (SISO) dynamic model for each robot link (with decoupled assumption). Table 2 shows the frequency response data collected for Joint 1 of one MENTOR robot in order to obtain the actual SISO model. The obtained model was used to design the phase-lead controller via frequency response approach.

Table 2: Data collected (Joint 1)

f (rad/s)	f (Hz)	v_i (V)	Θ_o°	Θ_o / v_i	$20\log(\Theta_o / v_i)$ (dB)	$t\Delta$	T*	Φ
0.3	0.04775	255	452	1.77255	4.97197	-5.357	20.944	-92.08
0.35	0.0557	255	381	1.49412	3.4877	-4.63	17.952	-92.848
0.4	0.06366	255	353	1.38431	2.82469	-4	15.708	-91.673
0.5	0.07958	255	263	1.03137	0.26831	-3.246	12.566	-92.991
0.6	0.09549	255	233	0.91373	-0.78369	-2.744	10.472	-94.332
0.7	0.11141	255	184	0.72157	-2.83445	-2.382	8.976	-95.535
1	0.15915	255	142	0.55686	-5.08504	-1.68	6.2832	-96.257
1.3	0.2069	255	106	0.41569	-7.62469	-1.309	4.8332	-97.5
1.5	0.23873	255	94	0.36863	-8.66825	-1.14	4.1888	-97.976
2	0.31831	255	63	0.24706	-12.144	-0.8825	3.1416	-101.13
2.5	0.39789	255	49	0.19216	-14.3269	-0.7263	2.5133	-104.03
4	0.63662	255	37	0.1451	-16.7668	-0.4924	1.5708	-112.85
6	0.95493	255	21	0.08235	-21.6864	-0.3728	1.0472	-128.16
10	1.59155	255	13	0.05098	-25.8519	-0.2614	0.6283	-149.77
12	1.90986	255	10	0.03922	-28.1308	-0.2137	0.5236	-146.93
15	2.38732	255	10	0.03922	-28.1308	-0.2053	0.4189	-176.44
16	2.54648	255	9	0.03529	-29.046	-0.1986	0.3927	-182.06
17	2.70563	255	8	0.03137	-30.069	-0.1756	0.3696	-171.04
18.5	2.94437	255	7	0.02745	-31.2288	-0.1843	0.3396	-195.35

Figure 7 shows the Bode plot capturing the frequency response of one of the joint (joint 1) of the MENTOR robot arm derived from the experimental data tabulated in Table 2.

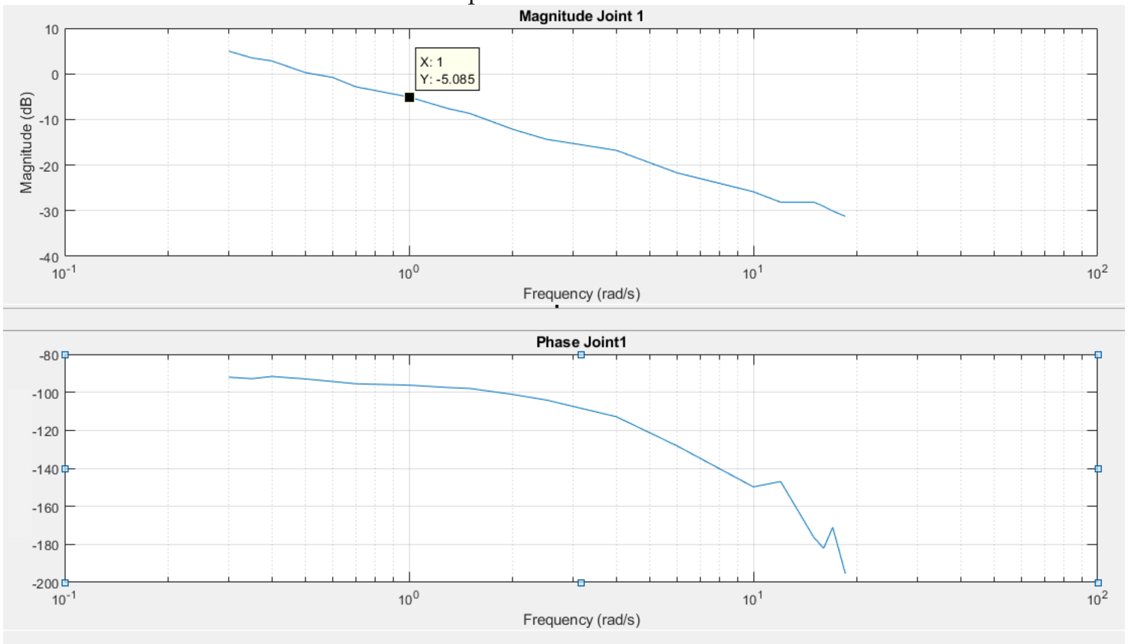


Fig 7 Bode Plot showing the magnitude and phase of the frequency response of Joint 1.

From Figure 7, the DC gain and the pole of the system was obtained as in (1)-(4).

$$20\log\Delta k = -5.085dB \quad (1)$$
$$\Delta k = 0.5568 \quad (2)$$

$$\text{Pole} = 8 \text{ rad/s} \quad (3)$$

$$G_{uncomp}(s) = \frac{0.5568}{s(s+8)} \quad (4)$$

The subsequent methodology to design phase-lead control was observed. The phase margin of the uncompensated system is 19.7°. The recommended phase margin was set to 45°.

$$\begin{aligned} D_{lead\_J1(w)} &= \frac{1}{\beta}\left(\frac{\omega+\omega_l}{\omega+\omega_h}\right) \\ &= \frac{1}{0.2675}\left(\frac{\omega+16.2919}{\omega+60.9043}\right) \\ &= \left(\frac{0.06138\omega+1}{0.01642\omega+1}\right) \end{aligned} \quad (5)$$

The phase-lead controller design is discretized using bilinear transformation in (6).

$$w = \frac{T}{2}\frac{(z-1)}{(z+1)} \quad (6)$$

Substituting (6) into (5) yields,

$$D_{lead}(z) = \frac{1}{0.2675}\left(\frac{\frac{T}{2}\left(\frac{z-1}{z+1}\right)+16.2919}{\frac{T}{2}\left(\frac{z-1}{z+1}\right)+60.9043}\right) \quad (7)$$

Setting the sampling time to be *T=0.01* sec,

$$D_{lead}(z) = \frac{16.2969z+16.2869}{16.2932z+16.2906} \quad (8)$$

Figure 8 shows the MATLAB® SISO tool being used to validate the compensated system (only for joint 1). It is evident that the designed phase-lead controller improves the phase margin of the closed-loop system for each dynamic link whilst meeting the transient requirement.

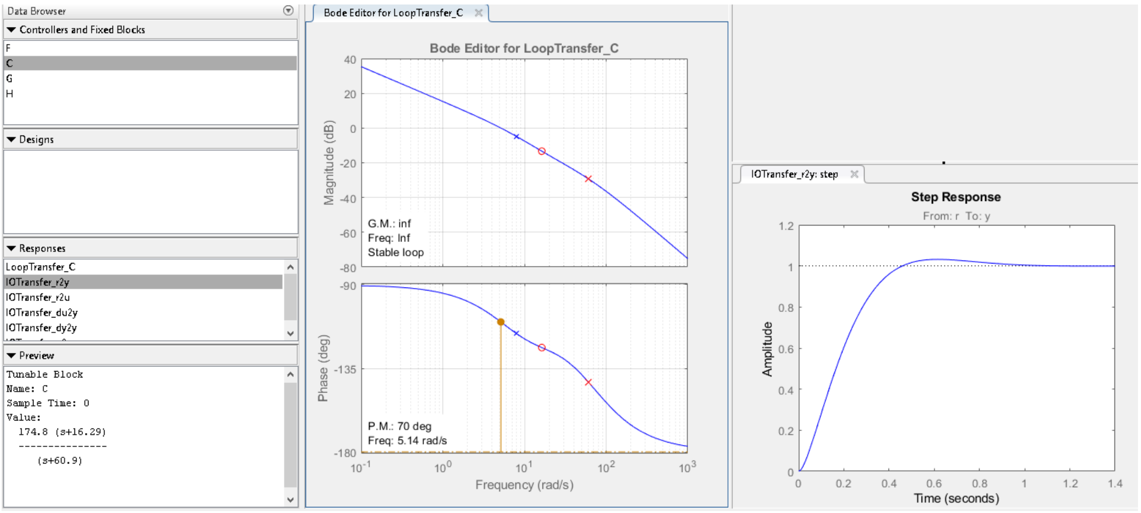


Fig. 8: Compensated Bode Plot (Joint1)

4.0 HARDWARE IMPLEMENTATION

Figure 9 shows the synchronization error between the Master unit and the respective MENTOR robot 1 and robot 2. The synchronization error was data-logged via MATLAB® using the HIL approach.

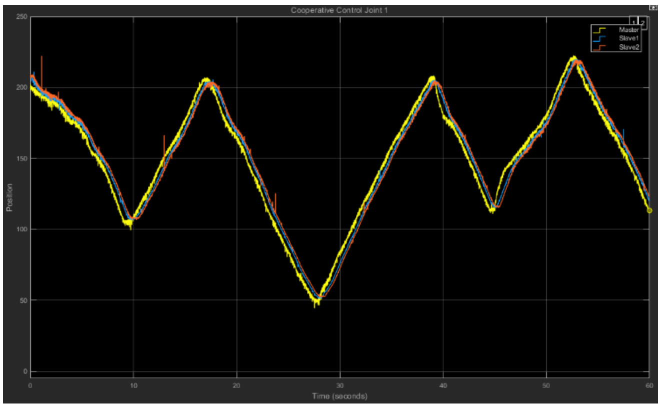
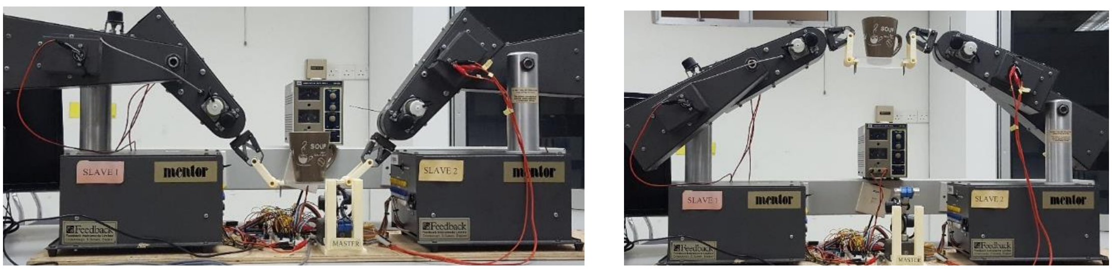


Fig. 9 Tracking error between Master unit-Slave 1 and Slave 2.



(a) (b)

Fig. 10 The delicate Cooperative task; balancing a cup filled with water starting at (a) initial position and ended up at the (b) final position.

Figure 10 shows the screenshot of the experiment conducted to illustrate the cooperative task, i.e., to delicately balance a cup filled with water on a tray whilst moving from initial position (Figure 10(a)) to its final position (Figure 10(b)).

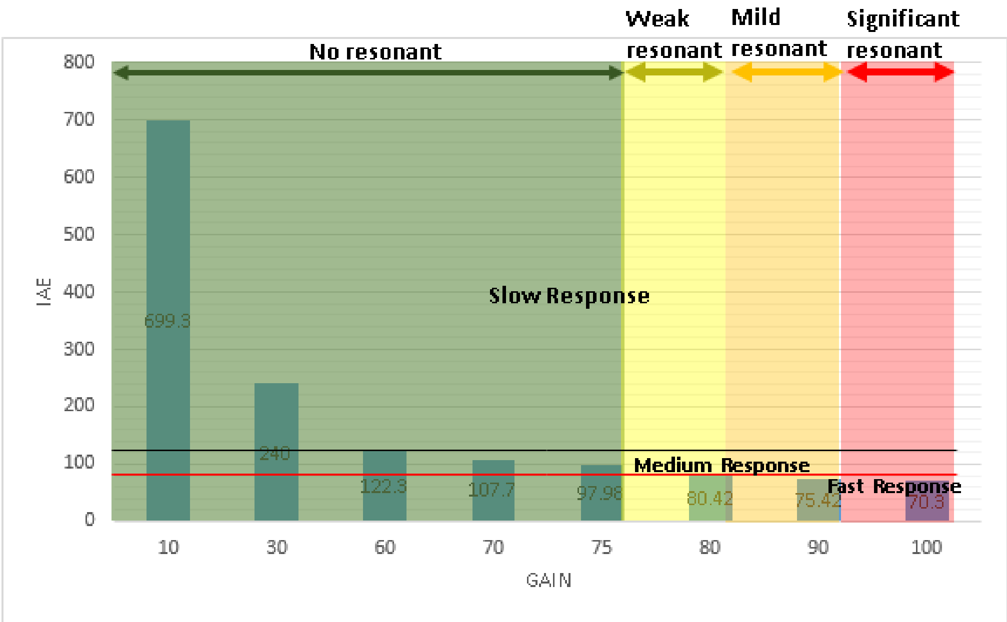


Fig. 11 Integral Absolute Error for Robot Link 1

Figure 11 shows the computed Integral Absolute Error for Robot Link 1, i.e. the synchronization error between the Master unit and the Agent robot unit (one of the MENTOR robot). The discrete phase lead control gain can be adjusted for fast response. However, it is apparent to witness that the fast response of the robot link motion is desireable but at the expense of resonant (intermittent vibration) occurring. This was largely attributed by the bandwidth of the DC motor of the associated robot link. The robot link motion can be commanded at a slower pace to allow the resonant to dissipate completely. However, this may cause the agent robot to lag behind the Master unit, i.e., the sluggish performance (high IAE), as a consequence, may deter the cooperative objective of balancing the cup (filled with water), resulting spillage. A compromise need to be made when selecting the gain of the discrete phase-lead controller.

5.0 CONCLUSION

The objective to design and develop a cooperative control to control two industrial robotic arm for cooperative task has been achieved. Under the decoupled assumption, each link of the robot can be modeled as a separate SISO system. The SISO models for both robotic arms were obtained through experimental frequency response procedure. Using the derived model, the discrete phase-lead controller for each joint has been designed using the frequency response approach. The synchronization error signals were derived taking angular position feedback from the neighbouring robotic arm and cross feed to the robotic arm so that the discrete phase-lead controller function cooperatively. By using MATLAB Simulink, the parameter can be varied in real time for further tuning. The result of the parameter change can be observed immediately after it was applied in MATLAB Simulink workspace. Future work in the area of adaptive control and compliance can be further introduced in particular to compensate for varying load as well as to ensure the huma-robot safety aspect in the industrial production line.

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