ICEM 12-13 November, 2016. ISBN:978-93-86256-11-9

Force Control of Robot Manipulator using Industrial Servo Drives*

Arun Dayal Udai[1], Subir Kumar Saha[2], Ravi Prakash Joshi[3] and Rattan Sadanand[4]

***Abstract*— Force control is a prerequisite to perform compliant manipulation tasks like surface finishing, assembly task, cooperative robot based manufacturing, etc. Moreover, as these tasks require close interaction with the environment, any inaccuracy may lead to loss of life and property. Most of the conventional hardware controller that exists in the industry do not support implementation of current or torque control at any robot joints so as to have an end-effector force control. The paper proposes an use of a direct torque control (DTC) using an industrial AC permanent magnet synchronous motor (PMSM), which was implemented on a 2-link robot arm developed in-house. The proposed system has the capability to be used for end-effector force control apart from being used for obtaining joint compliance of an industrial robot.**

I. INTRODUCTION

Industrial robots are brute machines that can only be programmed for its end-effector pose, i.e., position and orientation, or for its joint angles. Once commanded it applies its full potential to execute the desired command without considering any obstacles on its way. This is a serious problem with any industrial robot as it can cause severe damage to the robot or its environment. With the increasing demand of industrial robots to perform robotic assembly, cooperative manipulation, end-effector or link level interactions with environment, pure position control strategy turns out to be inadequate. The robots now are expected to sense any external force and take corrective measures to finally execute the desired instructions.

Having a joint torque control at the robot joints has been proven to be instrumental in designing force control algorithms for research robots. A good number of these approaches like stiffness, impedance, admittance, hybrid controls have been discussed by [1], and a variety of such robots was commercialized for domestic environment. However, these robots are not common in the industry due to its low precision, smaller payload capacity, less ruggedness, and high initial capital cost. An industrial setup with open control architecture is considered paradigm for the implementation of such interaction control [2]. However, any industrial robot manufacturer restricts the access to robot's intrinsic control parameters for its joint servos, controller gains, dynamic constants like mass moment of inertia and link masses, etc., probably to maintain its finely tuned safety and quality standards. Industrial robots are powerful and are meant to perform precise tasks with strict quality standards. Any mishandling may cause immense damage to the environment and property. These restrictions have proven to be major hindrance towards the development of robots for specialized applications like compliant manipulation and interaction control or more formally for *force control*. This resulted in a very few literature on force control of industrial robots. Schutter and Brussel [3], suggested a controller design which was based on an external force control loop that was closed around the robot's existing positioning system. As the basic architecture of the robot was still position controlled, the robot failed to detect and enact against any link collisions. A disturbance-observer was proposed by [4] instead of the use of force sensors suggested by previous researchers. The advantage was proven while establishing a mechanical contact, where the usage of standard force sensor is limited due to its narrow frequency band of sensing, soft mechanical structure, and its noisy information. A disturbance observer was retrofitted over an industrial robot to establish a stable contact. Such a huge rework with a custom made controllers are normally difficult to achieve with a variety of industrial robots available nowadays. Khatib et. al. [5] presented a concept of torque-to-position transformer that allowed joint-torque control based force controller schemes to be implemented as a software unit to any conventional joint position-controlled industrial robot. With the knowledge of a joint-position servo controller and the closed-loop frequency response each joint torque commands are converted to instantaneous joint displacements. Having such intrinsic information about standard industrial robots is normally not possible. KUKA LWR iiwa robot reported by [6], Rethink® robotics 'Sawers' robot, ABB® YuMi and few others are some of the reference platforms that supports joint torque control and compliant manipulation. However, its new economically viable designs are still awaited that can handle heavy industrial loads with an expected precision.

With the development of power semiconductors, microelectronics and industrial grade micro-computers, AC servo drives have evolved to a highly coupled, non-linear, multivariable structure and is now effectively being used in sophisticated, real-time, and complex industrial applications [7]. PMSM drives are widely used in robotics with the configuration commonly known as field-orientation control (FOC), which has a nested current, velocity and position

* The reported research was carried out under a sponsored project funded by BARC/BRNS, Mumbai at Indian Institute of Technology Delhi, India.

[1]Arun Dayal Udai is an Assistant Professor in the Department of Mechanical Engineering, BIT Mesra, Ranchi, India. arun_udai@bitmesra.ac.in

[2]Subir Kumar Saha is a Professor in the Department of Mechanical Engineering, IIT Delhi, India. saha@mech.iitd.ac.in

[3]Ravi Prakash Joshi is Master's student at Graduate School of Life Science and System Engineering, Kyushu Institute of Technology, Japan. joshi-ravi-prakash@edu.brain.kyutech.ac.jp

[4]Rattan Sadanand is Master's student at Department of Mechanical Engineering, Johns Hopkins University, Baltimore, US. ratan.sadan@gmail.com

loops. It provides a fast dynamic response with decoupling [8] and allows high-performance torque control. Advanced PMSM drives are now used in robotics as a Direct Torque Control (DTC) drives that compare to DC motors in terms of performance, torque response, and accuracy of speed-control [9], [10]. This paper demonstrates a representative design using PMSM actuators of a two-link manipulator that uses two Beckhoff® AC PMSM actuators that supports direct torque control and demonstrates the end-effector force control. The following subsections will elaborate upon different subsystems of the designed compliant 2-link robot and the experimental results.

II. Beckhoff® Servo Drive and Motor-gear Unit

The PMSM actuator along with the servo amplifier is known as servo drive. A compact drive system $EL7201$ manufactured by Beckhoff® was procured which implements the control system based on *field-orientation control* (FOC). The monitoring of numerous parameters such as overvoltage and undervoltage, overcurrent, terminal temperature or motor load via the precise motor model, offers maximum operational reliability. Figure 1 shows the connection of the motor resolver, brake and the phase wires to the servo amplifier. The servo amplifier was interfaced to an Industrial PC (IPC) through a high speed Ethernet protocol $EtherCAT$® which allows a rated speed and current control frequency of $16kHz$ and $32kHz$, respectively. Table I lists the connecting wires of the PMSM actuator phase, brake and the resolver to the servo amplifier.

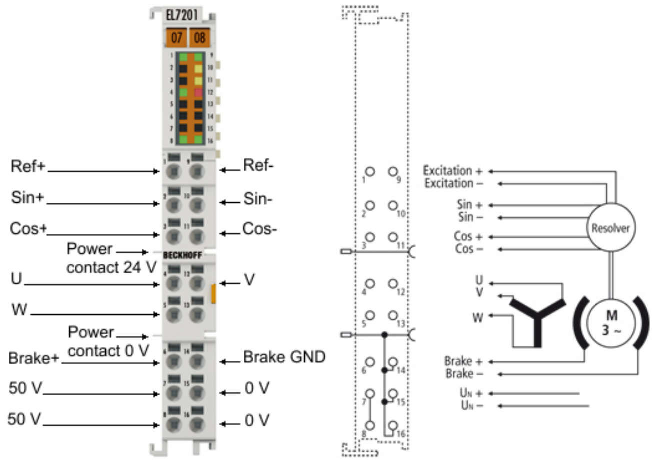


Fig. 1: Connection of PMSM and the EL7201 drive

The actuator was selected so as to drive the 2-link robot with the specifications discussed in section V with a maximum tip velocity of 2 m/s in velocity control mode. Such speed is comparable to any standard industrial robot. In order to do so, a PMSM $AM8131$ from Beckhoff® was procured whose specifications are listed in Table II. The gear reduction ratio was kept to minimum so as to have a better torque reflectance while the robot manipulator is in motion and also during standstill condition when the manipulator joint axes were acted upon by the gravity torques only. This

TABLE I

Servo Drive EL7201 connections

Terminal point	Name	Comment
1	Ref +	Resolver excitation +
2	Sin +	Resolver sine +
3	Cos +	Resolver cosine +
4	U	Motor phase U
5	W	Motor phase W
6	Brake +	Motor brake +
7	50 V	DC link supply + (8...50 V)
8	50 V	DC link supply + (8...50 V)
9	Ref -	Resolver excitation -
10	Sin -	Resolver sine -
11	Cos -	Resolver cosine -
12	V	Motor phase V
13	n.c.	not connected
14	GND	Motor brake GND
15	0 V	DC link 0 V supply
16	0 V	DC link 0 V supply

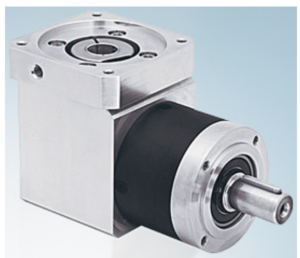
allowed back-drivability which is a pre-requisite for any direct-torque controlled manipulator. With the available set of compatible gear-boxes and taking the manipulator design into consideration an angled planetary gear unit $AG2250$ of Beckhoff® with gear-ratio of 10 and rated torque of 15 Nm was chosen. Figure 2 shows the actuator and the gear units used for the robot.

TABLE II

Specifications of AM8131 PMSM actuator

Data for 50V DC	AM8131-0F01
Rated torque	1.35 Nm
Rated speed	1000 min^{-1}
Rated power	0.14 KW
Peak torque	6.07 Nm
Standstill current	5.0 A
Peak current	27.8 A
Torque constant	0.27 Nm/A
Voltage constant	19 mV/min^{-1}
Number of poles	8
Rotor moment of inertia	0.462 $kgcm^2$

(a) PMSM actuator (AM8131)



(b) Angled planetary gearbox (AG2250)

Fig. 2: Actuator and gear units

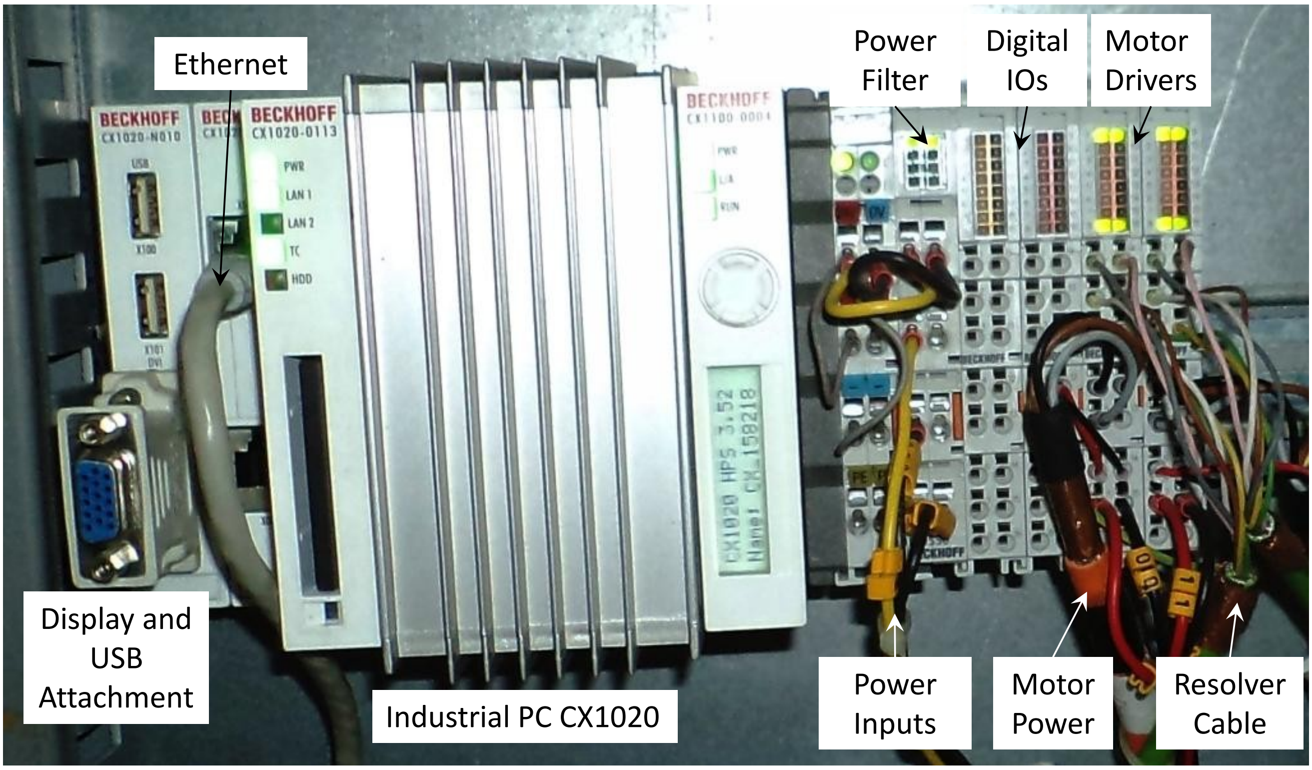


Fig. 3: IPC (CX1020) with accessories.

III. TwinCAT® Real-time Driver and IPC

In order to assign real-time capability to a standard Ethernet port of an IPC controller, Beckhoff TwinCAT® 2.0 was installed under Microsoft® Windows environment. TwinCAT allows a Programmable Logic Controller (PLC) based instructions for implementing any controller using the servo drives. Instructions for installation and commissioning of TwinCAT may be found in [11]. However, a pre-installed TwinCAT version 2.0 on an IPC, i.e., $CX1020$, with $24V$ power-supply, and surge filter ($EL9550$) was used in this work. The technical specifications of the IPC are listed in Table III. Figure 3 shows the IPC with its accessories.

TABLE III
Technical specifications of the IPC

Technical data	CX1020-0113
Processor	Intel Celeron® M ULV, 1 GHz clock frequency
Flash memory	128 MB Compact Flash card (bootable)
Internal main memory	256 MB DDR RAM
Interfaces	2 × RJ45 (Ethernet, connected to PC)
Operating system	Microsoft Windows Embedded CE 6
Control software	TwinCAT 2.0 PLC runtime
System bus	16 bit Industry Standard Architecture (ISA)

Once all the drives and the real-time driver were installed, they were configured to accommodate the PMSM drives as joint axes. This was done by importing the pre-compiled version of XML file supplied with the motors that included the extrinsic parameters, like rated current, thermal constants, number of pole pairs, torque constants, rotor moments of inertia, winding inductances, control gains for current and velocity loops, motor speed limitation, application delays, etc. Apart from these a TwinCAT configuration manager was installed on a standard non-realtime PC. This can communicate to the IPC through standard Ethernet cable. Using this the extrinsic control parameters, encoder resolution, gear ratio, and corresponding scaling factors, etc. were configured for the controller.

IV. Interfacing Industrial PC through C# .Net

In order to have a programming flexibility, the entire motion controller was programmed using Microsoft Visual Studio C# .Net programming language on a standard desktop PC which was connected to the IPC via a standard Ethernet cable. The Application Programmers Interface (API) supplied by Beckhoff®, namely, `TwinCAT.Ads.DLL`, was used in C# that allowed the control variables available in the hardware controller within TwinCAT system running on the Industrial PC (IPC) to be accessed, and modified from the C# environment. This required the linking and defining the control parameters of the TwinCAT function blocks programmed separately and embedded into the IPC server. Using the TwinCAT configuration tool, the servo drive $EL7201$ was set to run in cyclic synchronous torque mode

(CST) using the method discussed in [11]. The actual torque was set during runtime using *target torque* variable M [11], which was calculated using the following relation

$$M = \frac{Torque\ Actual}{1000} \cdot \frac{Rated\ Current}{\sqrt{2}} \cdot Torque\ Constant \tag{1}$$

where the *Rated Current* was scanned automatically by Twin-CAT configurator using the XML file of the PMSM entered earlier. This was discussed in section III. The parameter *Torque Constant* was obtained from the PMSM actuator's specifications given in Table II. The Graphical User Interface (GUI) for the torque mode driving of the 2-link robot actuators in torque mode developed during this research is shown in Fig. 4.

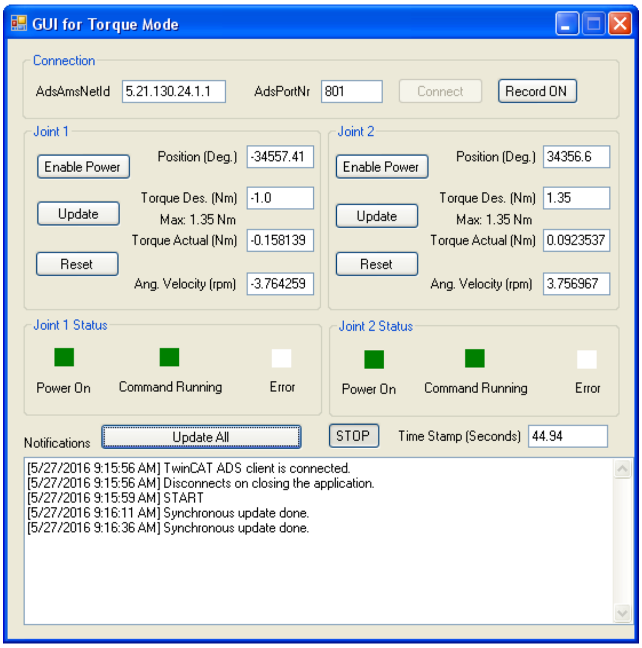
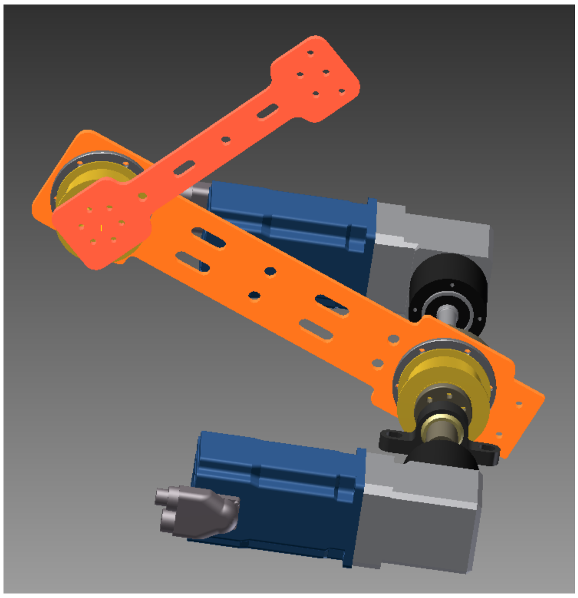


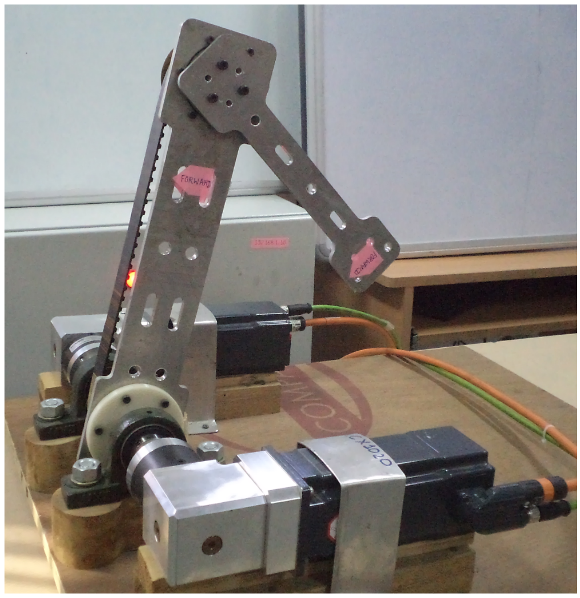
Fig. 4: Controller GUI for the 2-link robot

V. Mechanical Design of the 2-Link Robot Manipulator

The 2-link robot manipulator was initially designed so as to ensure the tip velocity of the second link to be 2 m/s, while the actuators run in velocity control mode. This is comparable to any standard industrial robot like KUKA KR5 Arc available in the Autonomous Systems Lab. (ASL) of BIT, Mesra. The link lengths were kept such that a minimum average torque is required for a given trajectory. The method was discussed in [12]. It was adopted to obtain the link lengths. However, the actual link lengths were based on the timing belt and the pulley size available in the market. The torque required in order to move a link at the required speed was decided in a way compatible to the industrial PMSM servo drive whose size and cost are least. Under these constraints, the link lengths were decided to be 295 mm and 220 mm. The couplers were also designed considering the size of the gearbox shaft, key-way and, the peak torque that the motor with the attached gearbox can deliver. The Computer Aided Design (CAD) assembly model of the 2-link manipulator is shown in Fig. 5(a), where the CAD models for the Beckhoff® actuators (Type: AM8131) and gearbox (Type: AG2250), and IGUS® bearings (Type: KSTM-18 Pillowblock and PRT-02-20-AL slewing ring) were obtained from the manufacturer's website. The completed mechanical assembly with the actuators are shown in Fig. 5(b).



(a) CAD assembly of the 2-link manipulator.



(b) Fabricated structure of the 2-link manipulator.

Fig. 5: Final design of the 2-link manipulator.

VI. Results and Discussions

In order to test the PMSM actuators independently for torque following without attaching them to the 2-links, a full-load and no-load tests were conducted. Figure 6 shows the experimental setup where one of the motor shaft was fully constrained to move, i.e., under full-load, and the second actuator was left free to rotate, i.e., under no-load condition. Figure 7 shows the variation of actual torque

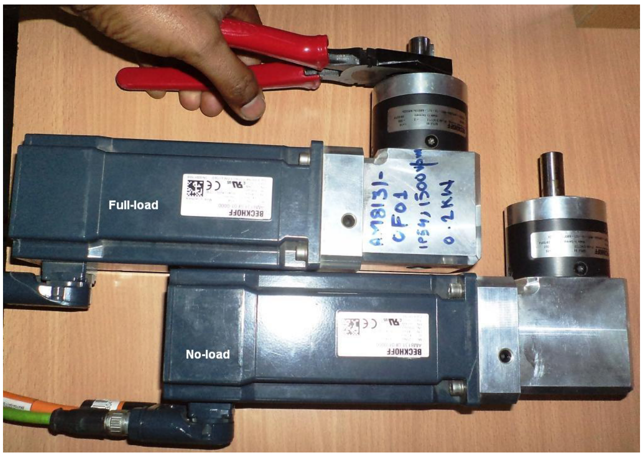


Fig. 6: Actuators in full-load and no-load conditions

with respect to the desired torque under no-load condition. It may be noted that the actual torque was obtained from the Beckhoff® PMSM servo controller where it uses an electromechanical model of the attached motor known to the controller, based on its run-time parameters like the armature current, temperature, etc. In case of full-load condition, it was observed that the actual torque achieves the desired torque, as indicated in Fig. 8. Small jitters in the sensed torque may be attributed to the electrical noise sensed in the current measurements which was eventually used for torque estimation. Figure 8 shows the variation of the actual torque with the desired torque in steps, where it was increased gradually to 0.4 Nm up till where the motor shaft can be held safely using the current test setup.

For no-load condition, the actual torque followed the desired torque until the armature reached its preset velocity of 176.88 rpm (0.402 $\times$ 440 along $Y-$axis in the Fig. 7) in the controller. The motor shaft remained stationary with zero velocity till 0.045 Nm of the applied torque due to inherent static friction of the components inside the actuator, as can be seen at 17.69 s. of Fig. 7 and then increased with the increase in desired torque until the motor shaft reached its preset velocity at 47.5 s.

Further, the test was extended by attaching the actuators to the 2-link robot manipulator for which the setup is shown in Fig. 9. In order to vary the vertical end-effector force delivered by the 2-link robot, the torque at the joints were varied. The second link was locked in the vertical position by applying the brake of the actuator at joint 2 in order to avoid slippage on the glass surface of the weighing scale which displays the load at the tip of link 2 or the end-effector. The vertical force now depends only on the torque applied at the first joint actuator. The torque τ_1 required to produce any vertical force F at the end-effector can be expressed as, $\tau_1 = F\cos\theta_1 \times a_1/N_g$, where a_1 is the length of the first link, which is 0.295 m, N_g is the gear-ratio of the gearbox

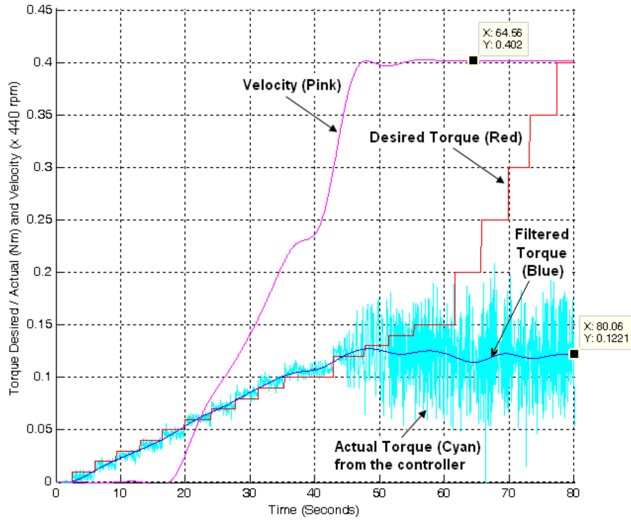


Fig. 7: Variation of torque under no-load condition

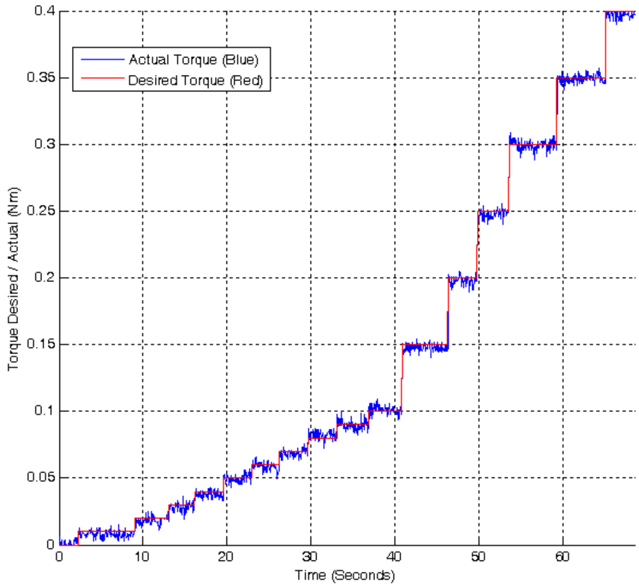


Fig. 8: Variation of torque under full-load condition

(10 in this case), and θ_1 is the angle subtended by the first link from the fixed horizontal base. For a given torque at the first joint the end-effector's vertical force was measured from a load measurement device, namely, weighing scale shown in Fig. 9. A comparison of the actual torque measured to the ideal torque required to produce a desired force is shown in Table IV. The deviation in the measured and ideal torques was mainly due to the masses of the links, bearings, belt, etc. that were neglected to calculate the ideal torque. With the above experiments done, it may be inferred that with precise kinematic and dynamic identifications Direct Torque Control (DTC) can be implemented in similar robots developed for any industrial applications that need to perform force-control tasks.

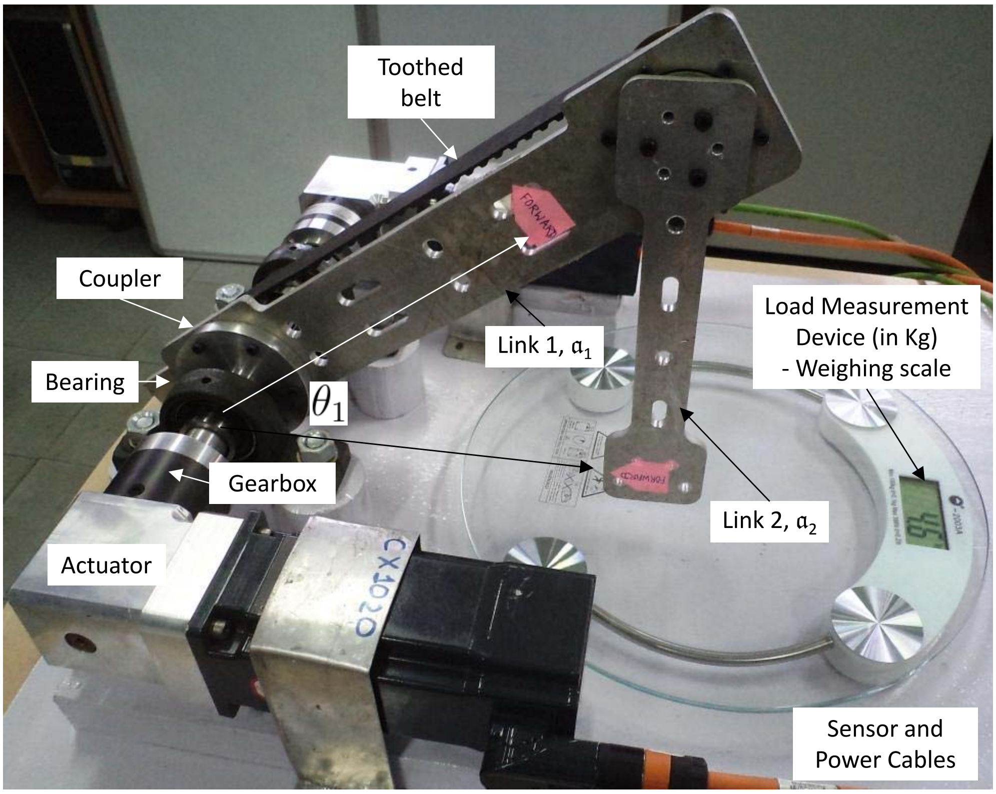


Fig. 9: Experimental setup of the two-link robot

TABLE IV
LOAD TESTING OF THE TWO-LINK ROBOT

Sl. No.	Measured force at end-effector (N)	Ideal torque at first joint (Nm)	Measured torque at first joint (Nm)
1	64.746	1.302	1.35
2	60.822	1.224	1.2
3	49.05	1.987	0.9
4	43.164	0.868	0.8
5	38.259	0.769	0.7

VII. Conclusion

This paper demonstrated control hardware implementations to achieve force/ torque capabilities in a robot without explicitly using a joint or end-effector force/torque sensor. The PMSM servo motor and its controller used in this work is useful for designing any robotic system performing compliant manipulation tasks. An AC Servo motor based 2-link robot manipulator was developed to illustrate the use of DTC. This design has the potential to be used for high-powered industrial robots with compliant motion capabilities with precision.

Acknowledgements

The authors sincerely acknowledge the technical inputs given by Mr. Abdullah Aamir Hayat, Ph. D. scholar of Program for Autonomous Robotics (PAR) Lab., IIT Delhi, India during design and fabrication of the developed 2 DoF robot.

References

[1] G. Zeng and A. Hemani, “An overview of robot force control,” *Robotica*, vol. 15(5), pp. 473–482, 1997.
[2] F. Caccavale, C. Natale, B. Siciliano, and L. Villani, “Integration for the next generation: embedding force control into industrial robots,” *IEEE Robotics Automation Magazine*, vol. 12, no. 3, pp. 53–64, 2005.
[3] J. D. Schutter and H. V. Brussel, “Compliant robot motion II. A control approach based on external control loops,” *Int. J. of Robotics Research*, vol. 7, no. 4, pp. 18–33, 1988.
[4] S. Katsura, Y. Matsumoto, and K. Ohnishi, “Modeling of force sensing and validation of disturbance observer for force control,” *IEEE Transactions of Industrial Electronics*, vol. 54(1), pp. 530–538, 2007.
[5] O. Khatib, P. Thaulad, T. Yoshikawa, and J. Park, “Torque-position transformer for task control of position controlled robots,” in *IEEE Int. Conf. on Robotics and Automation, 2008, (ICRA 2008)*, 2008, pp. 1729–1734.
[6] B. Rainer, K. Johannes, S. Guenter, K. Ralf, A. Albu-Schaeffer, B. Alexander, E. Oliver, H. Sami, S. Andreas, G. Gerhard, and H. Gerhard, “The KUKA-DLR lightweight robot arm - A new reference platform for robotics research and manufacturing,” in 41^{st} *Int. Symp. on Robotics (ISR) and* 6^{th} *German Conf. on Robotics (ROBOTIK)*, 2010, pp. 1–8.
[7] P. C. Sen, “Electric motor drives and control - past, present, and future,” *IEEE Transaction on Industrial Electronics*, vol. 37, no. 6, pp. 562–575, December 1990.
[8] T. M. Jhans, “Motion control with permanent-magnet ac machines,” *Proceedings of the IEEE*, vol. 82, no. 8, pp. 1241–1252, August 1994.
[9] ABB®, “ABB technical guide 1: Direct torque control,” ABB Oy, Tech. Rep., April 2002.
[10] T. Merentie, “ABB: direct torque control,” *Industrial Robotics*, vol. 22, no. 2, pp. 27–28, 1995.
[11] Beckhoff®, “EL72x1 servo motor terminals documentation,” Beckhoff Automation GmbH & Co. KG, Germany, Tech. Rep., 2016, version 3.0.
[12] W. A. Khan and J. Angeles, “The kinetostatic optimization of robotic manipulators: The inverse and the direct problems,” *Transaction on the ASME*, vol. 128, pp. 168–178, 2006.