Kinematic-Chain of an Industrial Robot and Its Torque Identification for Gravity Compensation

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***Abstract*— In this paper, an experimental method is proposed to identify the relationship between the actuator space and joint space of an industrial robot, KUKA KR5. The mathematical model in the form of matrix relating the actuator and joint space is termed as "structure matrix". This matrix is useful in identifying the robot's architecture for the transfer of motion. Further, the torques required to balance the robot against gravity was identified through Fourier series fit. For that, only the joints that are orthogonal to the gravity direction were considered as they influence the most. The identified joint torques were validated by considering different trajectories than those used to identify the necessary coefficients of the Fourier series.**

Keywords— Kinematic chain, Actuator and Joint spaces, Structure Matrix, Gravity Torque Identification

I. Introduction

Serial robots are widely used in industries to perform tasks such as welding, pick and place, painting, assembly of components, peg in a hole, etc. Most of these tasks require six-degrees-of-freedom (DOF), three for positioning and remaining three for orientating the end-effector in space. The motion is transmitted with the use of actuators and transmission systems (mostly gears, belts and pulleys) associated to each link. Mostly, each manipulator joint is driven by single actuator via gearbox. In some cases, there are redundantly driven joints where the motion of one joint is caused by two or more actuators due to mechanical coupling [1]. The effect of gear-box was described in [2]. The closed form description is necessary to evaluate the impact on the equation of motion induced by the geared actuators. A robot is typically loaded onto its joints by its moving links, whereas it is controlled at the actuator space. This requires a closed form kinematic relationship between joint motion and the actuator motion.

The serial kinematic chain of the robot manipulator requires a large amount of actuator torque and power to withstand the weight of the robot links. Gravity loading can account for a significant portion of actuator torque in static condition and thus in the majority of industrial tasks it needs to be compensated. The passive mechanical gravity compensation for robot manipulator is where a weight is added to bring the center-of-mass of a link coincident with the joint axis. Passive compensation with spring element was presented in [3]. The gravity compensation and compliance based force control of robot manipulator was presented in [4].

The philosophy of reductionism for analysing the system by looking at its individual components is vital for identification of the system. In [5] the gravity based autonomous calibration of robot manipulator is discussed by analysing the system by reducing it to individual components. Here one joint of a manipulator is rotated keeping rest of the joints locked for the identification of gravity torque. In order to perform active gravity compensation, it is necessary to identify a relation that estimates the torque at each joint as the robot moves. Fourier fit was proposed in [6] to estimate the joint trajectory as a finite sum of harmonic sine and cosine functions. Such estimate is useful in many applications. For example, in [7] such torque estimate was used to eliminate the gravity forces, whereas the same can be used for force reflecting devices like exoskeletons, haptic devices [8], tele-operation, master-slave manipulator, etc. The iterative scheme was proposed in [9] for generating gravity compensation of manipulators with unknown dynamic model at the desired points, using control with PD gains. The rigid body load identification using the wrist force torque sensor was proposed in [10].

In this paper, gravity torque compensation or the torque required to counterbalance the robot's weight in static condition is reported for KUKA KR5 robot shown in Figure 1. In Figure 1, Motor 1, 2, 3, etc., corresponds with the six-degrees-of-freedom (DOF) of the robot at hand. Note, however, that while first three motors, i.e., Motor 1, 2, and 3 independently drive the first three axes. The last three motors, namely, Motors 4, 5 and 6 combinedly affect the joint motions, i.e., motion of joint 6 is affected by movements of Motors 4, 5 and 6. As an illustration, of the proposed compensation, joints 2, 3, and 5 of KUKA KR5 which are orthogonal to the direction of the gravity for most of the industrial tasks were considered. The joints 2, 3 and 5 were provided with the sinusoidal angle input and variations of the joint torques were recorded from the robot's KRC2 controller. Next, the mass moment of each link was extracted based on the above Fourier fit. The method was useful in identifying the parameters of the robot, leading to a general relationship of torque and angle variation which is more generic. The identified parameters were validated with other trajectories by varying the initial and final joint angles.

This paper is divided into three sections. In Section II, the method for kinematic chain identification and the relationship in matrix form is presented. In Section III, data acquisition process of the joint variables with the corresponding torques a presented. Using these data, relationships between the torques and the angles are established which helped in determining the mass properties of the robot links. Validation and results with concluding remarks are presented in Section III (D) and IV, respectively.

II. KINEMATIC-CHAIN IDENTIFICATION

Typically, any robot is driven by the motor coupled with gear box located at the joints. Input to the drives of the motors is current, and output is joint torque. The method for identifying the kinematic chain of KUKA KR5 shown in Figure 1 is presented in this section.

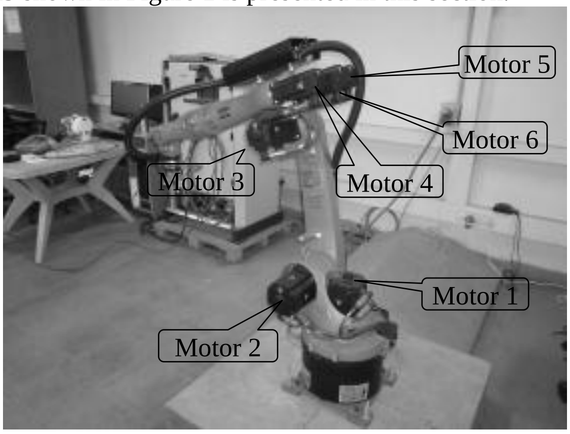


Fig. 1. KUKA KR5 robot

Note that KUKA KR5 is an industrial robot with six-DOF. The first three joints, namely, 1, 2, and 3 of KUKA KR5 have independent motors identified in Figure 1 as Motor1, Motor 2 and Motor 3. The last three joints, i.e., 4, 5 and 6, are actuated by Motor 4, Motor5 and Motor 6 of Figure 1, in some coupled manner. The couplings are schematically shown in Figure 2(b) and 2(c). The last three joints are interconnected such that the motion of the Motor 6 affects the motion of Motors 4 and 5 in order to compensate the motion of links 4 and 5. Hence it is useful to understand their kinematic relationship.

Figure 2 shows the schematic diagram of the joint drives. The motor current in amperes is denoted by i_i, whereas ε_i and φ_i denote the encoder values and angular displacement of the i^{th} motor, respectively. Moreover, the motor inertia is denoted by J_i, and θ_i is the joint angle. The relationship between the actuator space and the joint space can be represented as,

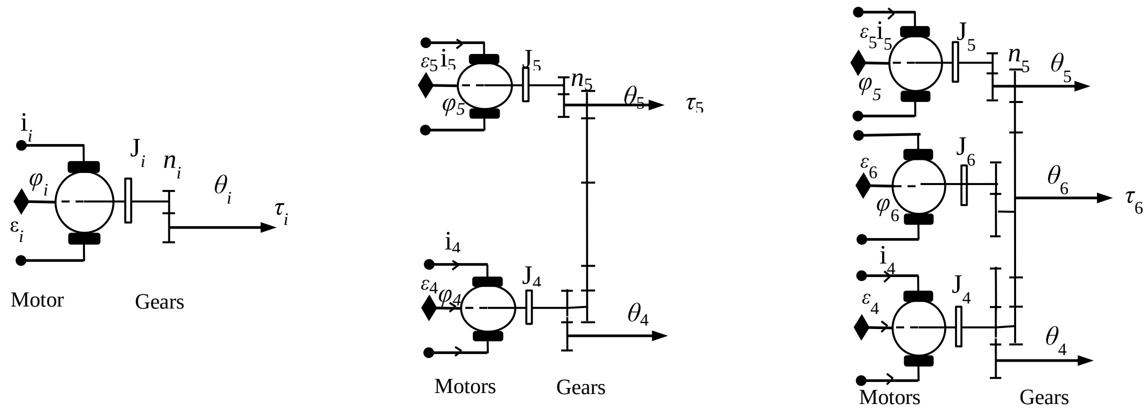
$$\boldsymbol{\varphi} = \mathbf{S}\boldsymbol{\theta} \tag{1}$$

where $\boldsymbol{\theta} \equiv [\theta_1, \cdots, \theta_6]^T$ is the 6-dimensional vector of joint angles, whereas $\boldsymbol{\varphi} \equiv [\varphi_1, \cdots, \varphi_6]^T$ is the 6-dimensional vector of the motor shaft rotations. The 6×6 matrix **S** is termed as the "structure matrix" relating the joint space with the motor space. The elements of the structure matrix are represented as,

$$\mathbf{S} \equiv \begin{bmatrix} s_{11} & \cdots & s_{16} \\ \vdots & \ddots & \vdots \\ s_{61} & \cdots & s_{66} \end{bmatrix} \tag{2}$$

To satisfy (1) the matrix **S** possesses the following properties:

- The structure matrix has full rank, i.e., rank(**S**) = 6. Moreover, the matrix is square. Hence, the determinant must be non-zero, i.e., det(**S**) $\neq$ 0.
- Non-zero elements in the off-diagonal terms represent the dependence of one joint on another.
- Each non-zero element of the matrix **S** indicates the gear reduction ratio from the motor rotation to joint-rotation

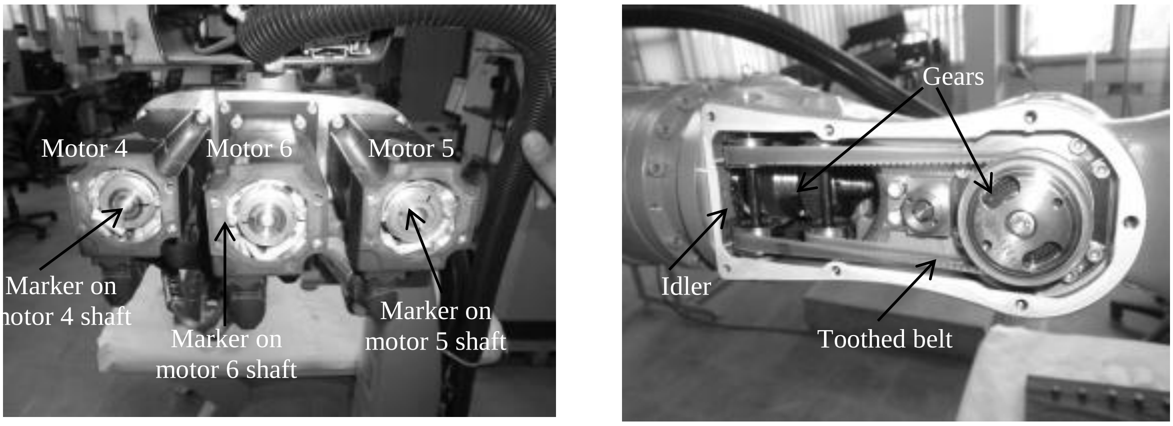


a) Driving mechanism for joint *i*, here *i* equal to 1 to 4.

b) Driving mechanism for joint 5.

c) Driving mechanism for joint 6.

Fig. 2. Schematic representation of joint motions of KUKA KR5 robot



a) Motors and markers on their shaft

b) Driving mechanism of wrist

Fig. 3. The driving mechanism of KUKA KR5

In order to identify the elements of matrix **S** for KUKA KR5, each joint was rotated one by one starting from the first to the sixth. Figure 3 shows the arrangement of the motors and encoders mounted for the last three joints, i.e., 4, 5, and 6, on the third link. Sixth motor is located at the center while 4th and 5th are placed to the left and right of it, respectively. The encoder counts are linearly related to the motor shaft rotation. To find the relationship between the encoder increment and the rotation of the motor shaft, the complete rotation, i.e., by 360 degrees was provided to the motor shaft and the encoder counts were noted from RSI. The full rotation was checked by the markers placed on the motor shafts as shown in Figure 3 (a). The joints meant for the wrist movement of the robot are driven a combination of twisted toothed belts with an idler and gears shown in Figure 3(b).

From Table I, the variation of motor rotations (φ_i*'s*) in degrees and the linear varying encoder counts (ε_i*'s*) can be related as,

$$\boldsymbol{\varphi} = \mathbf{T}_m \boldsymbol{\varepsilon} \qquad (3)$$

where, $\boldsymbol{\varphi} \equiv [\varphi_1, \; \cdots, \; \varphi_6]^T$, is the 6-dimensional vector of the motor rotations, $\mathbf{T}_m$ is the 6×6 constant diagonal matrix and $\boldsymbol{\varepsilon} \equiv [\varepsilon_1, \; \cdots, \; \varepsilon_6]^T$ is the 6-dimensional vector of encoder counts. Matrix $\mathbf{T}_m$ is obtained as,

$$\mathbf{T}_m = 360 \begin{bmatrix} \begin{matrix} 1/16385 & 0 & 0 \\ 0 & 1/16390 & 0 \\ 0 & 0 & 1/16386 \end{matrix} & \mathbf{O}_{3\times3} \\ \mathbf{O}_{3\times3} & \begin{matrix} 1/12300 & 0 & 0 \\ 0 & 1/12283 & 0 \\ 0 & 0 & 1/12284 \end{matrix} \end{bmatrix} \qquad (4)$$

where $\mathbf{O}_{3\times3}$ imply zeros of the off-diagonal elements. In (4) the denominators were obtained by taking the difference of the encoders count after each complete rotation and averaging it for the readings under encoder counts columns in Table I. Next to relate the encoder counts with joint readings, some simultaneous joint movement commands were given to the robot's controller. Corresponding encoder counts were recorded. They are tabulated in Table II based on which the following relationship is obtained:

$$\boldsymbol{\varepsilon} = \mathbf{T}_j \boldsymbol{\theta} \qquad (5)$$

TABLE I. MOTOR ROTATION ANGLE, ENCODER COUNTS AND JOINT ANGLES READINGS FOR SIX AXES OF KUKA KR5.

	Joint 1			Joint 2			Joint 3		
S. No.	Motor rotations (φ_1 in Degrees)	Encoder counts (ε_1)	Joint angle (θ_1 in Degrees)	Motor rotations (φ_2 in Degrees)	Encoder counts (ε_2)	Joint angle (θ_2 in Degrees)	Motor rotations (φ_3 in Degrees)	Encoder counts (ε_3)	Joint angle (θ_3 in Degrees)
1.	360	16419	2.89	360	16330	2.87	360	16427	4.15
2.	720	32795	5.76	720	32723	5.75	720	32794	8.28
3.	1080	49140	8.64	1080	49132	8.64	1080	49165	12.42
4.	1440	65577	11.53	1440	65537	11.52	1440	65564	16.56
5.	1800	81960	14.41	1800	81889	14.39	1800	81929	20.69
	Joint 4			Joint 5			Joint 6		
	(φ_4)	(ε_4)	(θ_4)	(φ_5)	(ε_5)	(θ_5)	(φ_6)	(ε_6)	(θ_6)
1.	360	12280	4.83	360	12287	8.53	360	12283	14.92
2.	720	24612	9.69	720	24570	17.05	720	24541	29.81
3.	1080	36874	14.31	1080	36856	25.57	1080	36840	44.75
4.	1440	49208	19.37	1440	49143	34.1	1440	49133	59.68
5.	1800	61481	24.2	1800	61420	42.62	1800	61419	74.61

where $\mathbf{T}_j$ is a 6×6 constant matrix, and $\boldsymbol{\theta}$ is defined after (1).

TABLE II. ENCODER COUNTS VERSUS THE JOINT ANGLES

Joint Space			Encoder Counts		
θ_4	θ_5	θ_6	ε_4	ε_5	ε_6
10	10	10	25410	10433	8232
20	10	30	50821	13653	24355
30	10	20	76231	13274	15782
10	20	30	25408	28444	25038
40	50	60	101641	70542	49734
50	40	60	127052	55751	49052
60	50	40	152460	69784	32587

Using the values of Table II, the elements of 6×6 matrix $\mathbf{T}_j$ can be obtained as follows:

$$\mathbf{T}_j = \begin{bmatrix} \begin{matrix} 5.68 & 0 & 0 \\ 0 & 5.68 & 0 \\ 0 & 0 & 3.95 \end{matrix} & \mathbf{O}_{3\times3} \\ \mathbf{O}_{3\times3} & \begin{matrix} 2.54 & 0 & 0 \\ -0.03 & 1.43 & 0 \\ -0.03 & 0.03 & 0.82 \end{matrix} \end{bmatrix} \qquad (6)$$

In (6), first four diagonal elements were found using the readings of Table I and noting the Independent joint relation as,

$$\varepsilon_4 = t_{44}\theta_4 \,,\, \varepsilon_3 = t_{33}\theta_3 \,,\; \varepsilon_2 = t_{22}\theta_2 \text{ and } \varepsilon_1 = t_{11}\theta_1 \qquad (7a)$$

where t_{ii} , for i=1, …,4 are the first four diagonal elements of matrix $\mathbf{T}_j$. The other non-zero elements of $\mathbf{T}_j$ in (6) were evaluated using the readings of Table II and noting the coupled relation for wrist action as,

$$\begin{aligned} \varepsilon_6 &= t_{64}\theta_4 + t_{65}\theta_5 + t_{66}\theta_6 \\ \varepsilon_5 &= t_{54}\theta_4 + t_{55}\theta_5 \end{aligned} \qquad (7b)$$

where t_{54}, t_{55}, t_{64}, t_{65} and t_{66} are the non-zero coefficients of $\mathbf{T}_j$, which were found by substituting at seven readings of Table II in (7b) and taking generalized inverse of the associated coefficient matrix. On combining (3) and (5), $\boldsymbol{\varphi}$ is obtained as,

$$\boldsymbol{\varphi} = \mathbf{S}\boldsymbol{\theta}$$

$$\text{where, } \mathbf{S} = \mathbf{T}_m\mathbf{T}_j \qquad (8)$$

The 6×6 matrix **S** for KUKA KR5 is then found as,

$$\mathbf{S} = \begin{bmatrix} \begin{matrix} 124.92 & 0 & 0 \\ 0 & 125.05 & 0 \\ 0 & 0 & 86.98 \end{matrix} & \mathbf{O}_{3\times3} \\ \mathbf{O}_{3\times3} & \begin{matrix} 74.59 & 0 & 0 \\ -1.02 & 42.00 & 0 \\ -1.00 & 1.00 & 24.13 \end{matrix} \end{bmatrix} \qquad (9)$$

where $\mathbf{O}_{3\times3}$ is the 3×3 matrix of zeros. The magnitude of non-zero elements in the first four rows of **S** in (9) gives the gear reduction ratio for the first four joints of the robot. Similarly, the sixth row with three non-zero elements represents the coupling of joint 6 by Motors 4, 5, and 6. The fifth row with two non-zero elements represents the coupling effect, i.e., joint 5 is driven by Motors 4 and 5. The negative sign represents the motion is coupled with an opposite rotation of the motors. For example, the element s_{64} = -1 of (9) represents that the 4th motor will rotate in the opposite direction to provide rotation to the 5th joint. Equation in (8) and (9) are important in identifying the kinematic chain of the KUKA KR5, which can be utilized for any kinematic, dynamic identification motion simulation, etc.

III. GRAVITY TORQUE IDENTIFICATION

The torque due to gravity at each joint of the robot dominates the torque required to drive the joints. In this section, a methodology is proposed to relate the joint torques with the corresponding joint angles. Figure 4 shows the CAD model of KUKA KR5 with its axes indicated with A_1, ..., A_6. Note that the 2nd, 5th and joints are orthogonal to the gravity vector, as shown in Figure 4.

A. *Formulation*

The joint torque and angular position values were obtained from the robot's sensory interface (RSI) as explained in the next section. To estimate the variation of the torques with respect to the angles, the joints were provided with periodic motions. Motions were given to joints 2, 3 and 5 only as they are always orthogonal to the gravity vector.

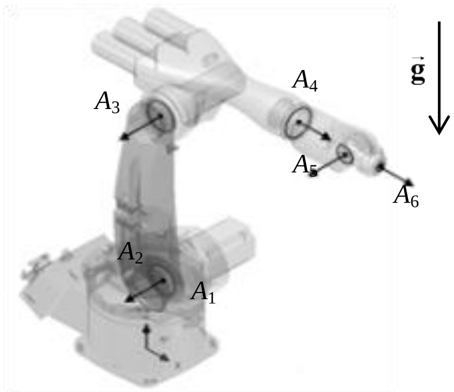


Fig. 4. Model showing the axis of the robot and the gravity vector.

Figure 5 shows a generic link, say, #*i* of a robot. According to the DH convention [12], #*i* is between joints *i* and (*i* +1), whereas # (*i*-1) connects the joints, (*i*-1) and *i*. Let $\mathbf{o}_i$ and $\mathbf{o}_{i-1}$ be the position vectors of the origins of #*i* and #(*i*–1), i.e., O_i and O_{i-1}, respectively, where the joints are coupling the links. Let $\mathbf{a}_{i-1}$ denotes the position vector of the origin of #*i* with respect to #(*i*-1) and $\mathbf{d}_i$ be the vector joining the origin O_i to the center of gravity of the #*i*, which is indicated in Figure 5 as C_i.

Actuator torque for the i^{th} revolute joint, τ_i , can be obtained by projecting the driving moments onto their corresponding joint axes, namely,

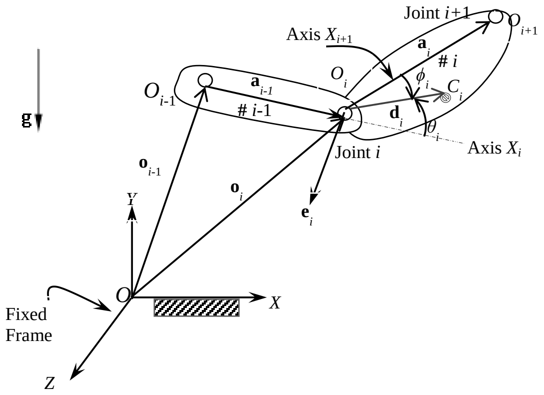


Fig. 5. Coupled links of a robot

For static moment due to gravity only, i.e., $[\mathbf{n}_{i,i+1}]_i$ is given by,

$$\tau_i = [\mathbf{e}_i]_i^T [\mathbf{n}_{i,i+1}]_i \;:\; \text{for a revolute joint} \tag{10}$$

where $[\mathbf{n}_{i,i+1}]_i$ is the moment on #*i* by #(*i*+1) which is represented in Frame *i* whereas $[\mathbf{e}_i]_i$ is the unit vector parallel to the axis of rotation of the i^{th} joint represented in the i^{th} frame where it is simply $[\mathbf{e}_i]_i \equiv [0 \quad 0 \quad 1]^T$ [13].

$$[\mathbf{n}_{i,i+1}]_i = m_i \left[\mathbf{d}_i \times \mathbf{g}\right]_i \tag{11}$$

Expanding the vector representation in Frame *i*, (10), can be rewritten

$$\tau_i = m_i d_i g \sin(\theta_i \pm \phi_i) \tag{12}$$

Note that the expression of τ_i in (12) can be recursively from the outer link to the inner link obtained as

$$\tau_{i-1} = \tau_i + m_i \left[\mathbf{d}_i \times \mathbf{g}\right]_{i-1}^T \left[\mathbf{e}_{i-1}\right]_{i-1} \tag{13}$$

Equation (12) and (13) are the expressions which will be used in Section C.

B. Data Acquisition

The input required for the identification of mass moment is the torque and angular readings of the joints. An add-on to standard KUKA Robot Language (KRL), namely, the Robot Sensory Interface (RSI), was used to obtain the coordinates of the end-effector in real time. This allows one to obtain different run-time parameters like joint angles, end-effector positions, gear torques, motor currents, etc., with the time. The PC was connected to KUKA controller using a standard Ethernet cable, also which is shown in Figure 6.

Note that the RSI was connected to the RSI object ST_MONITOR using ST_NEWLINK command as shown in Figure 6. The object ST_MONITOR sends the values joint angles to the PC, where a server application for monitoring, namely, RSIMonitor.exe was executed.

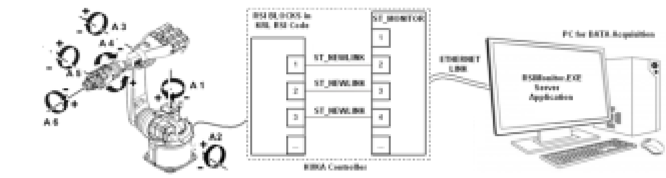


Fig. 6. Data acquisition system

Figure 1: Data acquisition system

The programme was then used to record the joint angles and its corresponding torques with respect to time in seconds. The communication was done at every twelve milliseconds. The measurements were taken by moving the 5th, 3rd and 2nd joints one after another as per the values shown in Table III. The readings were taken at a very slow speed, so that the dynamic effect, i.e., the torque values due to link inertias, etc., is negligible on the joint torque readings. Once the monitoring was started with ST_SETPARAM and RSI was started using ST_ON command, the joints were moved along the defined path. Accordingly the joint angles and torques were received in the PC through ST_ACTAXIS and ST_GEARTORQUE commands.

TABLE III. JOINT MOTION PROVIDED TO EACH JOINT OF KUKA KR5

Joint No.	Joint 2 (Degrees)		Joint 3(Degrees)		Joint 5(Degrees)	
	Initial Position	Final Position	Initial Position	Final Position	Initial Position	Final Position
1.	90	90	90	90	90	90
2.	0	-90	-90	-90	-90	-90
3.	90	90	90	0	90	90
4.	0	0	0	0	0	0
5.	0	0	90	90	-90	90
6.	0	0	0	0	0	0

Figure 7 shows the joint angles and the corresponding torques coming at each joint. From the Figure 7, it can be observed that while a joint was moved the other joints were kept in locked positions.

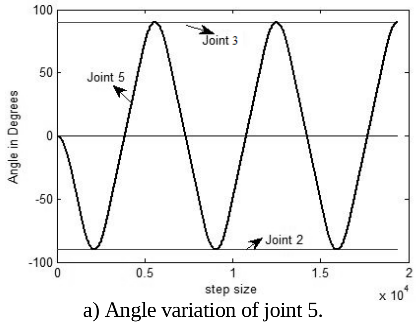
C. Identification of mass moment

From Figure 7, it is observed that the variation of the torques is sinusoidal in nature as the input sinusoidal joints were moved. Fourier approximation was used to best fit the curves [10],

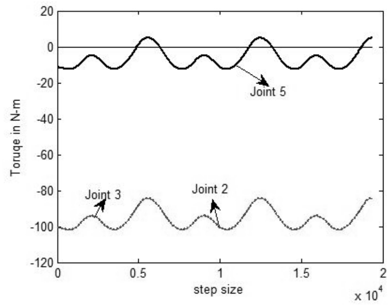
$$\tau_i = a_0 + \sum_{n=1}^{\infty} a_n \sin(n\beta) + b_n \cos(n\beta) \tag{14}$$

where τ_i is the torque at the i^{th} joint, moreover a_0, a_n, and b_n are constants, called the coefficients of the series and *n* is an integer, and β is the angle swept by the links. The first order approximation was taken by considering the value of *n*=1, in (14).

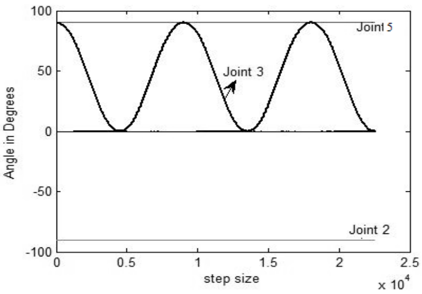
Using MATLAB `fit(x,y,fitType)` function, where x is the independent variable in this case (θ's) and y is the dependent variable here (τ's), whereas in fitType the Fourier fit with first order approximation was used [14].



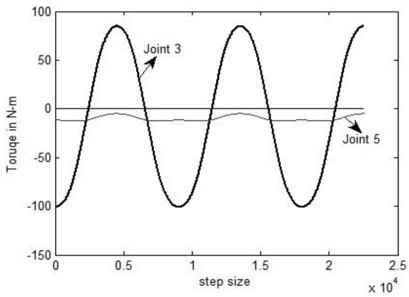
a) Angle variation of joint 5.



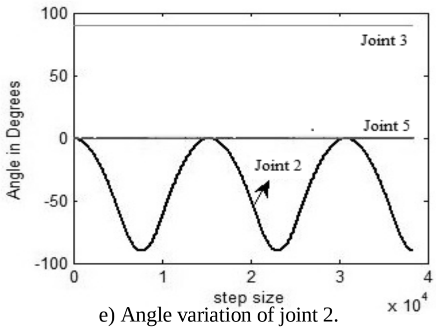
b) Torque variation of joint 2, 3 and 5.



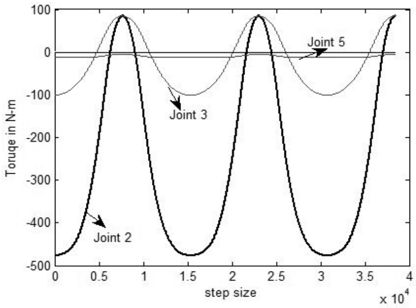
c) Angle variation of joint 3.



d) Torque variation of joint 2, 3 and 5.



e) Angle variation of joint 2.



f) Torque variation of joint 2, 3 and 5.

Fig. 7. Variation of angles and the corresponding torques at each joint

Since, the variation in joint angle 5 actually causes the variations of torques in link 5, 3 and 2 as evident from Figure 7(b), (d) and (f). The variation of τ_5 is written as a function 5th, 3rd and 2nd joint angles which is given as,

$$\begin{aligned} \tau_5 &\equiv f(\theta_5, \theta_3, \theta_2), \\ \tau_5 &= -0.052 - 11.47\cos(\theta_5 + \theta_3 + \theta_2) + 4.9\sin(\theta_5 + \theta_3 + \theta_2) \\ &\approx -11.47\cos(\theta_5 + \theta_3 + \theta_2) + 4.9\sin(\theta_5 + \theta_3 + \theta_2) \end{aligned} \quad (15)$$

Since, magnitude of the coefficient a_0 is very small, which is the constant torque required mainly to overcome the friction in the joints, is neglected for further use in the expression for τ_5. Hence the expression (15) has friction torque term appearing which has been neglected in order to account only for the gravitational torque coming on the links because of self-weight. Comparing (12) with (15), it was observed that the coefficients of sine and cosine can be physically represented as the components of the mass moment of the linkages. Table IV enlists the identified mass moments of the linkages. d_{ix} and d_{iy} are the components of the vector $\mathbf{d}_i$ joining the origin and the center of gravity as shown in Figure (5). Similarly, the torques in joint 3 and 2 denoted with τ_3 and τ_2 were obtained using (10)

$$\tau_3 = -126.28\cos(\theta_3 + \theta_2 - 44.85) + \tau_5 \quad (16)$$

$$\tau_2 = -375.70\cos(\theta_2) + \tau_3 \quad (17)$$

Figure 8 shows the flowchart of the steps involved in the identification of the above torque expression for gravity compensation in control or for gravity balancing of the robot.

TABLE IV. MASS MOMENT PARAMETERS

Link	$m_i d_{ix} g$ [N-m]	Mass moment $m_i d_{ix}$	$m_i d_{iy} g$ [N-m]	Mass moment $m_i d_{iy}$
5	11.47	1.169	4.90	0.499
3	89.49	8.612	88.86	9.058
2	375.70	38.297	0	0

D. Results and Verifications

The obtained relations in (15), (16) and (17) are useful in predicting the torques required to maintain the pose of a robot against its own weight under the effect of gravity. The motion was provided to joint 5, 3 and 2 by varying the angles as listed in Table V. The values of the torques corresponding to the trajectory provided and the variations in the angles are recorded from the RSI. The variations in angles were then fed to the torque expressions found in

(15), (16) and (17). Figure 9 shows the plots of the torques obtained both from RSI and the actual. Both are in good match, which shows that the expressions are correct, and can be used for gravity compensation.

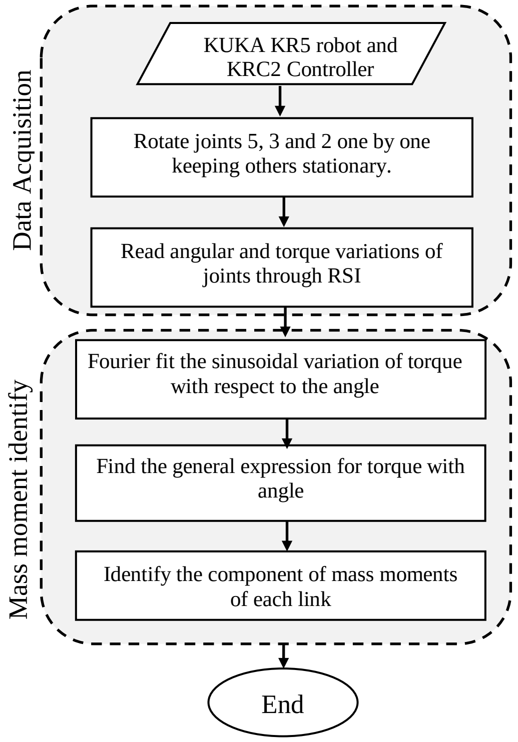


Fig. 8. Flowchart to identify gravity torque and mass moments

TABLE V. JOINT TRAJECTORY PROVIDED BY SIMULTANEOUSLY VARYING THE ANGLES

	Joint 1 (no motion)	Joint 2	Joint 3	Joint 4 (no motion)	Joint 5	Joint 6 (no motion)
Initial	90	-45	30	0	-90	0
Final	90	-90	50	0	90	0

IV. CONCLUSIONS

This paper presents two methodologies, one to identify the kinematic chain of KUKA KR5 and another to identify its necessary joint torques for gravity compensation. While the identification of kinematic structure is essential for various analyses of KUKA KR5, e.g., kinematic/dynamic identifications, motion simulation, etc., the torque identification is useful for gravity compensation. The algorithm for finding the mass moments of the links was also presented which is necessary to find the expression for the torques at each joint of the robot under study.

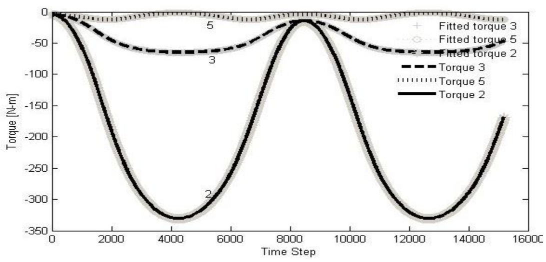


Fig. 9. Verification of torques values for a general trajectory

The relations are useful in predicting the torque required to keep the weight of the robot stationary at a pose under the action of gravity. The algorithm assumed that the encoder values, angular positions and joint torque readings are given accurately from Robot Sensory Interface (RSI) of the KUKA KR5 which interacts with the robots controller KR C2.

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