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Homogeneous transformation matrix for force-torque sensor orientation compensation in rotatable control handle

Shivam Suresh Zagade[1,2], Rajiv Basavarajappa[1], Sudhir Madhav Patil[1], Abhishek Pradeep Buzruk[2], Kshitij Ghanshyam Jiwane[2], Tole Sutikno[3,4]

[1]Department of Manufacturing Engineering and Industrial Management, COEP Technological University (COEP Tech), Pune, India
[2]Philips India Limited, Pune, India
[3]Master Program of Electrical Engineering, Faculty of Industrial Technology, Universitas Ahmad Dahlan, Yogyakarta, Indonesia
[4]Embedded Systems and Power Electronics Research Group, Yogyakarta, Indonesia

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ABSTRACT

The high inertia ceiling suspended systems with multiple degrees of freedom uses power assist technologies to reduce operator’s burden to operate the machine. Such systems are popularly used in medical diagnostic systems, construction machines, material handling, automotive, and aerospace assembly lines. These systems commonly use multi-axis force-torque (FT) sensor to sense the forces applied by user on rotatable control handle. These sensed forces are utilized by power assist algorithm to drive system in required direction with the help of electrical motor drives. The rotatable control handle used to control the machine poses a significant obstacle for maintaining alignment between FT sensor co-ordinate frame and the system’s base frame. This research paper focuses on the development of homogeneous transformation matrix to compensate for any change in FT sensor orientation caused by rotation of control handle. The homogeneous transformation matrix developed in this research paper, transforms the force and torque values measured by FT sensor with respect to system base frame. This adaptive technique provided seamless control of the power assist ceiling suspended system from different directions during handling and movement. This helped to enhance control and flexibility of power assist ceiling suspended system.

Corresponding Author:

Sudhir Madhav Patil
Department of Manufacturing Engineering and Industrial Management
COEP Technological University (COEP Tech)
Wellesley Road, Chhatrapati Shivajinagar, Pune-411005, Maharashtra State, India
Email: smp.prod@coeptech.ac.in

1. INTRODUCTION

The need for power assist systems in industrial, medical, aerospace, manufacturing, and material handling applications has gained considerable traction in recent years. The power assist systems are primarily designed and developed for reducing operator’s burden to operate high inertia machines. The power assist systems help to increase operational efficiency, enhance safety, and improve user experience. The recent developments and advancements in the field of power assist technology adapted in various sectors are discussed in this section.

a. Power assists systems

The power assist technologies commonly use force-torque (FT) sensor integration with user-friendly control handle. This provision helps to control and position high inertia ceiling suspended systems from multiple directions with the help of power assist algorithms [1]. Many researchers refer power assist system as force assist system. The motorized ceiling suspended system is an excellent example of force assist system. Jiwane *et al.* [2] developed force assist algorithm capable of integrating FT sensor with motor drive system to control the movement of system according to force applied by user on human machine interface (HMI) or control handle. In the study carried out by Patil *et al.* [3], the force and torque values measured by the FT sensor were further processed to reduce the crosstalks and signal noise. The processed and calibrated force and torque values were compared with absolute values to calculate required duty cycle for pulse width modulation (PWM) motor control.

Power assist technologies are widely used in surgical robots to increase surgical precision and patient's outcomes. These systems use multi-axis FT sensor, helps surgeons to perform critical surgeries with greater accuracy and precise control. The haptic devices developed for minimum invasive surgeries (MIS) have proven to be effective in enhancing efficiency of surgeons. For example, in robot-assisted surgeries FT sensors provide real-time feedback to surgeons, helping them to control and perceive forces exerted on tissues during delicate surgeries [4]. The joysticks are specially designed to control surgical robots to have better control and adaptivity during medical operations [5]. The use of power assist systems extended numerous opportunities to improve clinical accuracy, reduce human errors, enhance patient's safety, and comfort [6].

Power assist systems play a crucial role in the manufacturing sector. Power assists systems in assembly lines contribute to enhanced productivity, product quality, and workers safety. In the automotive manufacturing sector power assist systems help workers in critical assemblies with greater accuracy, thereby reducing errors and assembly time. Power assists systems help to improve ergonomics by reducing physical strain on workers and operators, consequently reducing the risk of injuries, and promoting a safer workplace environment [7]. The intelligent power assisted devices (IPAD) and intelligent assistive systems (IAS) developed provide deep insights on collaboration of human operator and intelligent machines [8]. The FT sensor feedback techniques, sophisticated electrical drive units and robust application-oriented programming contribute to the development of intelligent collaborative systems.

Collaborative robots (cobots) are deployed across diverse industries such as consumer goods, electronics, manufacturing, material handling and food processing units [9]. Cobots equipped with sensors can detect and respond to human stimulus. This helps in providing safe and seamless collaboration between human operators and robots in shared workspaces [10]. The use of concepts like rail based cobotic systems can be employed for heavy material displacement and can significantly reduce burden of workers thereby increasing work efficiency and safety [11]. In warehouses and distribution centres, robotic arms optimize tasks such as palletizing, pick-and-place, and sorting [12], [13]. The assistive devices such as hoist and cranes, exoskeletons and specially designed ergonomic handles for pallet control used for manual material movement, help in reducing the operator burden and enhances work efficiency [14]. The fundamental research done in the field of assistive devices focuses on flexibility, stability of interaction, low impedance rendering, and safety [15].

b. Multi-axis FT sensor

The need for force sensing and control is increasing drastically for robotic systems, intelligent assist systems and power assist systems. Such demands can be fulfilled with the help of multi-axis FT sensors. These sensors can easily be accommodated in any application because of their robust and adaptive design. The research done on development of FT sensors majorly focuses on enhancing measuring capability and sensitivity of sensors by improving the structural design. The different structural designs like three and six degree of freedom cross beams, column type sensors, column beam sensors, and Stewart platform sensors were developed based on application and functional requirements [16]. The multi-axis FT sensors are available in multiple sensing technologies like capacitive, magnetic, ultrasonic, piezoelectric, optical and force sensitive resistors (FSR). The capacitive type and strain gauge type sensing technologies are widely used in commercial multi-axis FT sensor [17], [18]. In industrial robotics application it is important to accurately measure the forces occurring in more than one spatial direction. FT sensor can measure three orthogonal forces (F_{xs}, F_{ys}, and F_{zs}) and three orthogonal torques (T_{xs}, T_{ys}, and T_{zs}) along its three-dimensional cartesian co-ordinate system also called as sensor co-ordinate system (x_s, y_s, and z_s) as shown in Figure 1.

These measured force and torque are processed by signal conditioning unit to reduce any kind of noise and errors occurred during measurements. The different sensor manufacturers integrate this signal conditioning and transmission units inside the sensor itself making it more versatile and compact. This makes multi-axis FT sensors as a suitable choice for robotic applications like measuring wrist and joint forces in industrial robotics, compliance control and collision detection [19], [20]. The multi-axis FT sensor developed for humanoid robot's feet to measure the contact forces, helps to adapt the uneven terrains and is effective in walking stability control [21]. FT sensor used on cobot's bedplate helps to detect collisions [22].

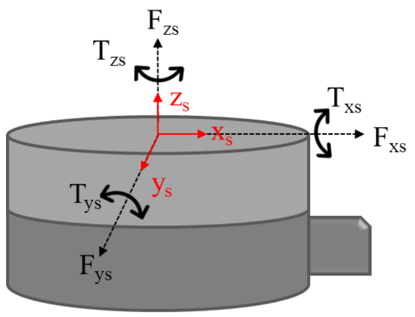


Figure 1. Three-dimensional cartesian co-ordinate system of FT sensor

c. Problem description

This research paper discusses a power-assist ceiling-suspended system that combines a multi-axis FT sensor with a rotatable control handle. Serving as both the control mechanism and HMI, the control handle is mounted on the FT sensor via a specially designed bracket. This entire assembly, including the control handle and FT sensor, is mounted on a height-adjustable column, which is suspended from the ceiling-suspended system. This control handle can be rotated in horizontal and vertical direction to achieve different orientations to provide convenient handling of the system. The operator applies a minimum amount of driving force on the control handle to move the system in desired direction in three-dimensional linear space. The force applied (F_a) on control handle is sensed by the multi-axis FT sensor in the form of forces and torques along the sensor co-ordinate frame. As per existing requirement of system only forces measured by FT sensor are primarily utilized by power assist algorithm to move system in three-dimensional linear space. The torque measured by the FT sensor are to be considered secondary. The power assist algorithm controls the speed and direction of ceiling suspended system based on magnitude and direction of force applied by user on control handle. The physical movement of system is achieved with the help of electrical motor drive controlled by power assist algorithm through PWM control technique. The general block diagram of power assist ceiling suspended system is shown in Figure 2.

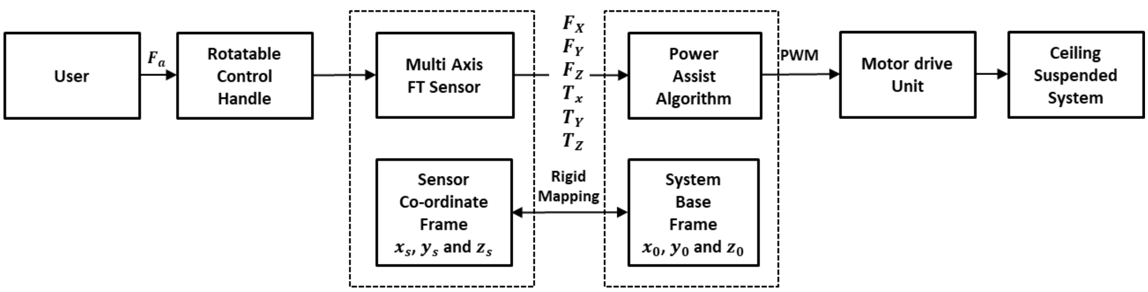


Figure 2. The general block diagram of power assist ceiling suspended system

This research paper addresses the scientific question: how to compensate for changes in the orientation of a multi-axis FT sensor, due to the rotation of a control handle in a power-assist ceiling-suspended system, to enable seamless control in multiple directions regardless of the handle's orientation? The sensor co-ordinate frame is rigidly mapped with the system co-ordinate frame in existing power assist ceiling suspended system i.e., x_0 is mapped with z_s, y_0 is mapped with y_s and $-z_0$ is mapped with x_s. The system co-ordinate frame is referred as system base frame and denoted as x_0, y_0, and z_0 as shown in Figure 3. The sensor co-ordinate frame is denoted as x_s, y_s, and z_s, also shown in Figure 3. However, a significant challenge arises when the user rotates the control handle. This causes a change in orientation of sensor co-ordinate frame with respect to the system base frame as shown in Figure 3. Therefore, the existing rigid mapping fails to compensate for this change in orientation of control handle and FT sensor. This demands need for development of homogeneous transformation of forces to compensate for the change in sensor orientation due to rotation of control handle. This compensation is important to ensure the system's capability to move and control in the different intended direction, irrespective of the control handle's orientation. The problem of sensor orientation compensation with respect to system base frame is significant and under development, leading to a research gap in the development of effective compensation technique for change in the control handle's orientation.

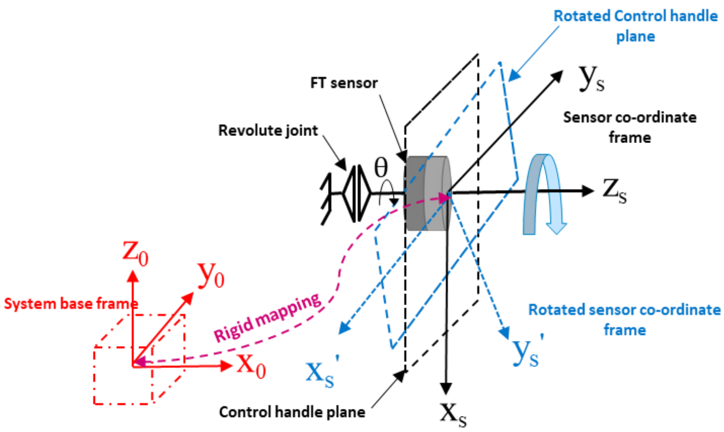


Figure 3. Illustration of change in sensor co-ordinate frame orientation with system base frame due to rotation of control handle

d. Rationale for the study

This research paper focuses on high-inertia, ceiling-suspended systems with multiple degrees of freedom, utilizing power-assist technology to alleviate the operator's effort in handling the machine. The power-assisted ceiling-suspended system presented here incorporates both a FT sensor and a rotatable control handle. When the operator applies force to the control handle, the FT sensor detects these forces, which are then processed by a power-assist algorithm to guide the system in the direction of the applied force.

In its current design, the power-assisted ceiling-suspended system can only be controlled from the control handle's initial orientation. This limitation arises due to the rigid mapping between the sensor's coordinate frame and the system's base frame, as outlined in the problem description section of the paper. This rigid mapping creates a challenge when the control handle rotates, causing a shift in the FT sensor's orientation. Addressing this issue - compensating for the FT sensor's orientation changes due to control handle rotation - is essential for enhancing the system's ability to move effectively in various directions, regardless of the control handle's position.

This paper focusses on developing a solution to address orientation compensation challenges encountered in FT sensors, specifically when used within a rotatable control handle system. This study aims to improve the accuracy and reliability of measurements in systems where orientation changes impact the sensor's data output.

The study investigates that how to apply homogeneous transformation matrices to accurately adjust for orientation discrepancies caused by handle rotation, thereby ensuring that the sensor readings remain consistent regardless of handle position. By integrating this matrix-based approach, the study provides a robust framework that enables real-time orientation compensation, which is essential for precision in various applications requiring dynamic control and measurement accuracy. This research contributes to advancements in sensor calibration techniques and offers practical insights for improving sensor-based control systems in environments where rotational adjustments are frequently required.

e. Study relevance

This research paper explores the ongoing development of a power-assist ceiling-suspended system. The current version of this system only allows control from a single, fixed orientation of the control handle, specifically its initial position. This limitation arises due to a rigid mapping between the sensor's coordinate frame and the system's base frame, as detailed in the problem description section. When the control handle is rotated, the orientation of the FT sensor shifts, posing a significant challenge in maintaining accurate control. Compensating for these changes in FT sensor orientation due to handle rotation is crucial to enhance the system's ability to operate smoothly in multiple directions, regardless of handle position.

To address this, a homogeneous transformation matrix has been developed for the existing rotatable control handle mechanism. This matrix transforms the force measurements from the FT sensor relative to the system's base frame. The power-assist algorithm then uses these transformed force values to move the system in the intended direction, adapting to the operator's applied force regardless of handle orientation. This adaptive method allows for intuitive and flexible control of the ceiling-suspended system from any direction, simply by rotating the handle. Such an approach offers significant potential in robotics and automation applications, addressing similar control challenges with enhanced usability and operational flexibility.

The study reported in this research paper is highly relevant as it addresses a critical challenge in precision measurement and control applications involving FT sensors. In many industrial, robotic, and biomechanical systems, FT sensors are integral for capturing accurate force and torque data. However, when these sensors are used within devices that incorporate rotational movement such as a rotatable control handle the orientation changes can cause significant measurement inaccuracies. These inaccuracies, if uncorrected, could lead to compromised system performance, control errors, and potentially costly outcomes in high-precision environments.

The authors' approach to developing a homogeneous transformation matrix to correct orientation-induced discrepancies ensures that the FT sensor's data remains accurate and reliable regardless of handle rotation. This capability is essential in applications where rotational adjustments are frequent, such as in robotic manipulators, medical devices, and other automated systems that rely on precise force-feedback for operational stability and safety. By offering a robust solution for real-time orientation compensation, this study contributes to improved sensor calibration methods and enhances the overall reliability of systems that depend on FT measurements.

In summary, the study is relevant as it directly addresses the need for advanced calibration and compensation techniques in scenarios requiring both high accuracy and adaptability to dynamic positional changes, making it valuable for a wide range of precision-demanding fields.

2. METHOD

2.1. Study approach overview

A homogeneous transformation algorithm has been developed to adjust for changes in the FT sensor's orientation caused by the rotation of the control handle. This algorithm enables dynamic alignment of the sensor's coordinate frame with the system's base frame, allowing the forces detected by the FT sensor to be accurately represented within the system's frame. As a result, operators can effectively control the system from various orientations of the control handle.

The transformation algorithm receives input from encoders located in revolute joints. This data is used to translate the forces measured by the FT sensor relative to the system's base frame. This design enables flexible control from multiple orientations of the rotatable control handle, enhancing user adaptability and operational precision.

A mathematical model is developed to accurately correct FT sensor data affected by handle rotation. Specifically, a homogeneous transformation matrix was created that adjusts for the orientation changes experienced by the FT sensor when the control handle rotates. This matrix transforms sensor measurements into a consistent reference frame, effectively eliminating errors caused by shifts in orientation. To achieve this, a systematic analysis was conducted of the FT sensor's behavior under various handle orientations, identifying the specific mathematical transformations needed to correct orientation-induced errors. The model is then validated through simulations and experiments that demonstrated the matrix's effectiveness in maintaining accurate sensor data, regardless of the handle's rotation angle. By implementing this transformation approach, a practical solution was provided to maintain data accuracy in applications where the sensor's orientation changes frequently. This work has broad applications in fields where precise force and torque measurements are critical, such as robotics, automation, and biomechanics.

2.2. Study approach rationale

A mathematical modeling approach was used to develop a robust solution for correcting orientation-induced errors in FT sensor measurements. Specifically, a homogeneous transformation matrix was constructed that can adjust the FT sensor data in real time based on the control handle's rotational changes. This matrix-based method provides a systematic way to map sensor measurements from the sensor's shifting orientation to a stable reference frame.

The approach included detailed analysis and derivation of transformation parameters to capture the impact of orientation variations on sensor readings. By employing this matrix, the authors were able to ensure that FT measurements remained accurate despite changes in the handle's orientation, which is particularly challenging in dynamic, real-world applications. The authors further validated their approach through simulations and experimental tests, confirming that the matrix effectively compensated for errors caused by orientation shifts. Following are the step-by-step details of the study approach rationale:

a. A homogeneous transformation algorithm was created to address the issue of FT sensor orientation changes in the rotatable control handle.
b. A kinematic diagram was developed for the control handle's rotating mechanism.
c. Using forward kinematics and rigid body transformation, the homogeneous matrix for the current control handle mechanism was determined.
d. This algorithm enabled the transformation of the sensor's coordinate frame relative to the system's base frame.

e. Consequently, forces applied to the control handle were accurately transformed with respect to the system's base frame across various handle orientations.
f. These transformed forces were then processed by the power-assist algorithm to move the system in the desired direction via electric motor drives installed on ceiling rails.

The rationale for this approach is based on the inherent challenges posed by orientation variability in control handles, where accurate sensor feedback is essential for maintaining precise force and torque measurements in dynamically shifting positions.

In previous research, conventional calibration methods were often insufficient for accounting for orientation changes during real-time operations. This limitation motivated the choice of a mathematical transformation framework, specifically using a homogeneous transformation matrix, due to its ability to seamlessly map sensor data between various rotational positions without requiring additional hardware modifications. By providing a standardized way to adjust measurements relative to different handle orientations, this approach allows for a robust and adaptable solution to orientation compensation.

The homogeneous transformation matrix approach was selected for its established effectiveness in spatial transformations, enabling consistent and accurate data interpretation regardless of the handle's rotation. This methodology, grounded in coordinate transformation principles, ensures that FT sensor readings remain stable and reliable, ultimately improving the control accuracy of systems relying on these readings. Additionally, this approach aligns with the goal of enhancing the sensor's adaptability, enabling it to be deployed in environments where dynamic and multi-directional handle adjustments are frequent, such as in robotics or automated machinery.

2.3. Forward kinematic

Forward kinematics is a key component in robotics that involves determining the orientation and position of sensor with respect to the system base frame [23]. In case of sensor orientation compensation forward kinematics can be used to estimate orientation of sensor co-ordinate frame with respect to the system base frame [24]. The general flow of forward kinematic analysis is shown in Figure 4.

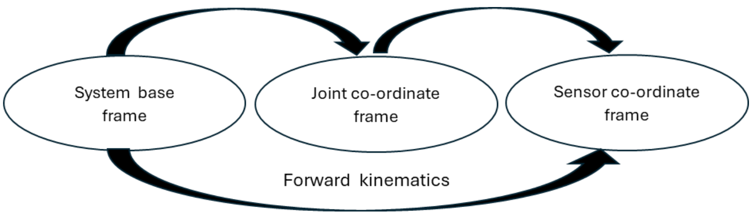


Figure 4. General block diagram for forward kinematics approach used in robotics

The process of forward kinematics involves development of kinematics diagram for given problem. The kinematics diagram allows us to breakdown complex robotic structure into simple joint-link diagram, improving understanding of the robotics structures and assigning co-ordinate frames to the joints [25]. This homogeneous matrix represents the transformation between two or more co-ordinates in three-dimensional space [26]. It combines both translation and rotation matrix. The general structure of homogeneous transformation matrix is as in (1):

$$H_n^{n-1} = \begin{bmatrix} R_n^{n-1} & T_n^{n-1} \\ 0\ 0\ 0 & 1 \end{bmatrix} \tag{1}$$

where, H_n^{n-1} represents general homogeneous transformation of n^{th} co-ordinate frame with respect to the $(n\text{-}1)^{th}$ co-ordinate frame. R_n^{n-1} represents rotation matrix of 3×3 size, which compensates for the change in orientation of one frame with respect to another. T_n^{n-1} represents translation matrix of 3×1 size, which compensates for the position of one frame with respect to other [27].

2.4. Development of kinematic diagram for rotatable control handle mechanism

Rigid body transformations were used in a conventional manner to develop the forward kinematic model. The mobile frames were assigned to each of the joints, allowing to apply forward kinematics to obtain a homogenous transformation matrix for each frame with respect to preceding frame. The kinematic diagram developed for a rotatable control handle mechanism and the co-ordinate frames assigned to every joint is shown in Figure 5.

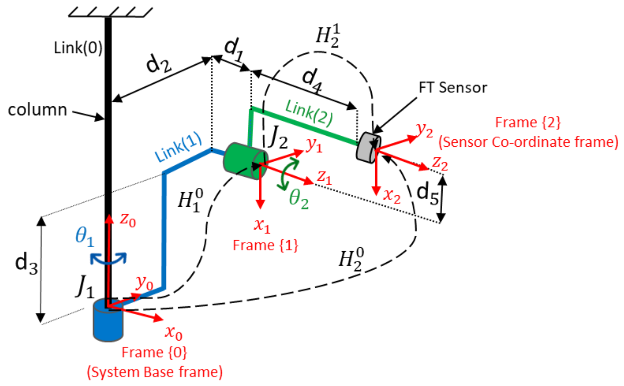


Figure 5. Kinematics diagram for rotatable control handle mechanism

The mobile co-ordinate frames assigned to the joints of kinematic chain are frame {0}, frame {1}, and frame {2} referred as system base frame, intermediate joint frame and sensor co-ordinate frame respectively. The kinematic links identified are discussed further. Link (0) represents system column around which control handle assembly can rotate, link (1) represents intermediate link, and link (2) represents sensor mounting bracket. Table 1 shows respective link lengths and offsets. The kinematic joints and their respective rotation angles for horizontal and vertical rotation of control handle are given in Table 2.

Table 1. Geometrical notations for link and their respective sizes

Link lengths	Values (mm)
d_1	200
d_2	500
d_3	600
d_4	500
d_5	100

Table 2. Kinematic joint notations and their respective ranges

Joint notation	Type of joint	Rotation angle	Ranges
J_1	Revolute joint	θ_1	0˚ to +180˚ (ACW) and 0˚ to −180˚ (CW)
J_2	Revolute joint	θ_2	0˚ to +90˚ (ACW) and 0˚ to −90˚ (CW)

2.5. Deriving forward kinematics for rotatable control handle mechanism

The orientation of FT sensor with respect to the system base frame is obtained from kinematics analysis of rotatable control handle mechanism. The classical rigid body transformation approach is used to derive kinematics equations. The equations given by (2) to (4) represent the individual rotation matrix R_x, R_y, and R_z respectively along x, y, and z axes [28]. In these equations S(θ) and C(θ) represent the short notations for sin(θ) and cos(θ) respectively.

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & C(\theta) & -S(\theta) \\ 0 & S(\theta) & C(\theta) \end{bmatrix} \tag{2}$$

$$R_y = \begin{bmatrix} C(\theta) & 0 & S(\theta) \\ 0 & 1 & 0 \\ -S(\theta) & 0 & C(\theta) \end{bmatrix} \tag{3}$$

$$R_z = \begin{bmatrix} C(\theta) & -S(\theta) & 0 \\ S(\theta) & C(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

Homogeneous transformation matrix H_1^0 given by (5) represents homogeneous transformation of intermediate frame {1} with respect to system base frame {0} as shown in Figure 5. The link (1) and link (0) make revolute joint (J_1) that can be rotated by an angle θ_1. Homogeneous transformation matrix H_1^0 for the intermediate frame {1} with respect to the system base frame {0} obtained is given by (6).

$$H_1^0 = \begin{bmatrix} R_1^0 & T_1^0 \\ 0\ 0\ 0 & 1 \end{bmatrix} \quad (5)$$

$$H_1^0 = \begin{bmatrix} 0 & -S\theta_1 & C\theta_1 & d_1 \\ 0 & C(\theta_1) & S(\theta_1) & d_2 \\ -1 & 0 & 0 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

Homogeneous transformation matrix H_2^1 given by (7) represents the homogeneous transformation of the sensor frame {2} with respect to intermediate frame {1} as shown in Figure 5. The link (2) and link (1) and link (2) make revolute joint (J_2) that can be rotated by an angle θ_2. Homogeneous transformation matrix H_2^1 for the sensor co-ordinate frame {2} with respect to the intermediate frame {1} obtained is given by (8).

$$H_2^1 = \begin{bmatrix} R_2^1 & T_2^1 \\ 0\ 0\ 0 & 1 \end{bmatrix} \quad (7)$$

$$H_2^1 = \begin{bmatrix} C(\theta_2) & -S(\theta_2) & 0 & -d_5 \\ S(\theta_2) & C(\theta_2) & 0 & d_6 \\ 0 & 0 & 1 & d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

The overall homogeneous transformation matrix H_2^0 represents the transformation of the sensor co-ordinate frame {2} with respect to the system base frame {0}. The overall homogeneous transformation matrix is obtained by multiplying individual homogeneous transformation matrix along the kinematic chain given by (9). The overall homogeneous matrix obtained is given by (10). The rotation matrix R_2^0 given by (11) is extracted from the overall homogenous matrix given by (10) to transform the forces and torque measured along the sensor co-ordinate frame with respect to the system base frame.

$$H_2^0 = H_1^0 H_2^1 \quad (9)$$

$$H_2^0 = \begin{bmatrix} -S(\theta_1)\,S(\theta_2) & -S(\theta_1)\,C(\theta_2) & C(\theta_1) & -d_6 S(\theta_1) + d_4\,C(\theta_1) + d_1 \\ C(\theta_1)S(\theta_2) & C(\theta_1)C(\theta_2) & S(\theta_1) & d_6\,C(\theta_1) + d_4 S(\theta_1) + d_2 \\ -C(\theta_2) & S(\theta_2) & 0 & d_5 + d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (10)$$

$$R_2^0 = \begin{bmatrix} -S(\theta_1)\,S(\theta_2) & -S(\theta_1)\,C(\theta_2) & C(\theta_1) \\ C(\theta_1)S(\theta_2) & C(\theta_1)C(\theta_2) & S(\theta_1) \\ -C(\theta_2) & S(\theta_2) & 0 \end{bmatrix} \quad (11)$$

The force and torque values measured by FT sensor with respect to the sensor co-ordinate frame are converted separately into force and torque matrix as given in (12) and (13). The transformation of force and torque matrix with respect to the system base frame is given in (14) and (15). The transformed force and torque matrix are given in (16) and (17) respectively.

$$F_s = \begin{bmatrix} F_{xs} \\ F_{ys} \\ F_{zs} \end{bmatrix} \quad (12)$$

$$T_s = \begin{bmatrix} T_{xs} \\ T_{ys} \\ T_{zs} \end{bmatrix} \quad (13)$$

$$F_t = R_2^0\ F_s \quad (14)$$

$$T_t = R_2^0\, T_s \quad (15)$$

$$F_t = \begin{bmatrix} F_{xt} \\ F_{yt} \\ F_{zt} \end{bmatrix} \quad (16)$$

$$T_t = \begin{bmatrix} T_{xt} \\ T_{yt} \\ T_{zt} \end{bmatrix} \quad (17)$$

2.6. Algorithm

When both the angles (θ_1 and θ_2) are zero the sensor co-ordinate frame gets mapped with the system co-ordinate frame to compensate for the sensor orientation for initial position. Whenever, a control handle is rotated the values of joint angles θ_1 and θ_2 gets changed. The values of the joint angles are measured by the encoders utilized by the homogeneous transformation block to get the transformed force and torque values with respect to the system base frame. The control algorithm to compensate for the change in FT sensor orientation for rotatable control handle for power assist ceiling suspended system is highlighted in Figure 6.

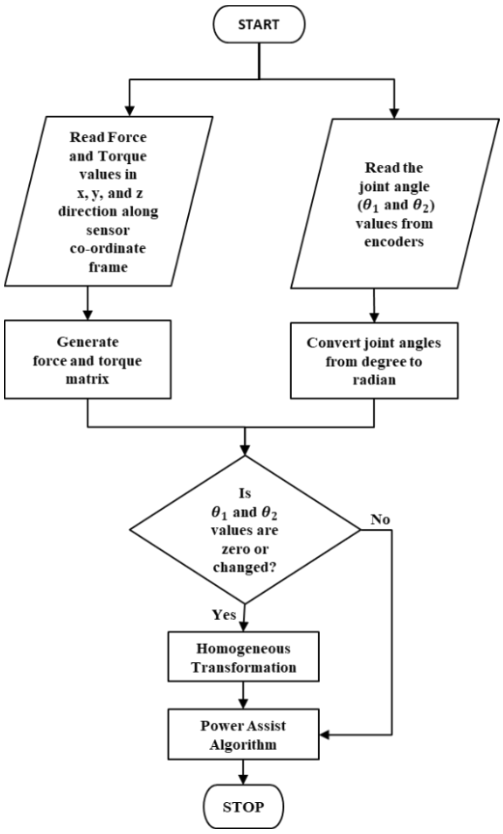


Figure 6. Control algorithm to compensate for the change in FT sensor orientation for rotatable control handle

3. RESULTS AND DISCUSSION

3.1. Experimental setup

The developed homogeneous transformation algorithm was tested for different orientations of rotatable control handle as given in Table 3. The pull and push forces were applied on the control handle in x_0, y_0, and z_0 directions along the system base frame with the help of digital force gauge (Make: IMADA, Model No. ZTA-500N) represented as F_a. To ensure repeatability and avoid human errors, the pull and push forces were applied twice with the help of digital force gauge during the test. The digital force gauge readings were recorded for different directions along the system base frame. The pull force (tension) applied by the force gauge is considered as positive and push force (compression) is considered as negative. As per the existing requirement of power assist ceiling suspended system, only forces are utilized for the movement of system. Therefore, scope of the results obtained is kept limited to transformation of forces only. The readings of forces measured by FT sensor before homogeneous transformation were recorded along the sensor co-ordinate frame and represented as F_{xs}, F_{ys}, and F_{zs}. The transformed values of forces are represented as F_{xt}, F_{yt}, and F_{zt} along the system base frame. The parameters and respective notations used for x, y, and z direction are given in Table 4. The functional diagram of experimental setup is illustrated in Figure 7.

Table 3. Different orientations of control handle

Orientation of control handle	θ_1	θ_2
Initial orientation	0˚	0˚
Standard orientation	+90˚	0˚
	–90˚	0˚
	+180˚ or –180˚	0˚
	0˚	+90˚
	0˚	–90˚
Intermediate orientations	0˚	+45˚
	0˚	–45˚
	+45˚	0˚
	–45˚	0˚
	+45˚	+45˚
	–45˚	–45˚

Table 4. Notation followed for experimentations and results

Sr. No.	Parameters	Notation
1.	x	x direction
2.	y	y direction
3.	z	z direction
4.	F_a	Force applied with the help of digital force gauge
5.	F_{xs}	Force measured in x direction of the sensor co-ordinate frame
6.	F_{xt}	Force transformed along x direction of the system base frame
7.	F_{ys}	Force measured in y direction of the sensor co-ordinate frame
8.	F_{yt}	Force transformed along y direction of the system base frame
9.	F_{zs}	Force measured in z direction of the sensor co-ordinate frame
10.	F_{zt}	Force transformed along z direction of the system base frame

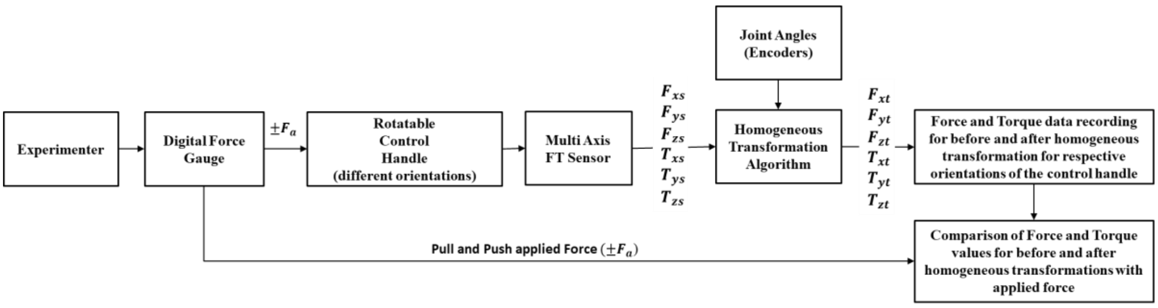


Figure 7. Functional diagram of experimental setup

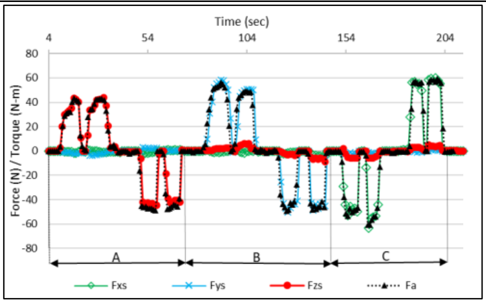
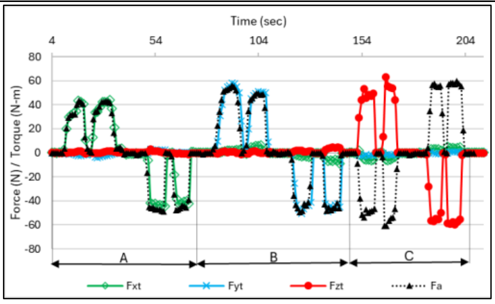
3.2. Results and discussion pertaining to various orientations of control handle

In this research paper the problem of compensating change in orientation of FT sensor due to the rotatable control handle is addressed. The homogeneous transformation algorithm developed in this research paper is capable of compensating for the change in orientation of FT sensor due to the rotatable control handle. The forces sensed by FT sensor with respect to the sensor co-ordinate frame are transformed with respect to the system base frame for different orientations of rotatable control handle given in Table 3. This technique allows the sensor co-ordinate frame to dynamically map with respect to the system base frame. The transformed values of forces were utilized by power assist algorithm to move system in respective direction along system base frame providing control and handling. The force values measured by FT sensor before homogeneous transformation and after homogeneous transformation compared with actual values of force applied by digital force gauge to validate the results. Results obtained for developed homogeneous transformation algorithm tested for multiple orientations of rotatable control handle (i.e., initial, standard and intermediate orientations) are discussed as follows.

3.2.1. Result and discussion for force transformation of initial orientations of control handle

When both the joint angles were zero (θ_1=0˚ and θ_2=0˚), the homogeneous transformation matrix aligned the sensor coordinate frame with the system base frame, as shown for the initial orientation of the control handle in Table 5. A comparative study was conducted on the forces sensed by the FT sensor before and after applying the homogeneous transformation, comparing them with the actual force applied using a digital force gauge. Figures in Table 5 depicts the comparison plots for FT sensor readings and force gauge readings before and after homogeneous transformation respectively for initial orientations of control handle. The operator-applied forces on the control handle, sensed along the sensor coordinate frame, were dynamically transformed relative to the system base frame. This allows power assist algorithm to utilize this transformed force values to drive power assist ceiling suspended system with respect to the system base frame for initial orientation of control handle. This allows the system to move in the intended direction of the force applied by the operator. Similarly, force transformations achieved for other control handle orientations are discussed as follows.

Table 5. Comparison of FT sensor readings and force gauge readings before and after homogeneous transformation for initial orientations of the control handle

Sr. no.	Angles	Before homogeneous transformation	After homogeneous transformation
1.	θ_1=0˚ and θ_2=0˚	 A. F_a force applied in x direction along the system base frame is sensed by F_{zs} component of the sensor co-ordinate frame. B. F_a force applied in y direction along the system base frame sensed by F_{ys} component of the sensor co-ordinate frame. C. F_a force applied in z direction along the system base frame is sensed by F_{xs} component of the sensor co-ordinate frame.	 A. F_a force applied in x direction of the system base frame is transformed from F_{zs} into F_{xt} along the system base frame. B. F_a force applied in y direction of the system base frame is transformed from F_{ys} into F_{yt} along the system base frame. C. F_a force applied in z direction of the system base frame is transformed from F_{xs} into F_{zt} along the system base frame.

3.2.2. Result and discussion for force transformation of standard orientations of control handle

The standard orientations of control handles were achieved by rotating control handle by θ_1=0˚, ±90˚, +180˚, and θ_2=0˚, ±90˚. This causes changes in orientation of FT sensors (i.e., sensor co-ordinate frame) with respect to system base frame as shown in Figure 3. The homogeneous transformation algorithm dynamically maps sensor co-ordinate frame with respect to the system base frame allowing operator to control system from standard orientations as well, which was not possible in case of rigid mapping. This transformation helps to compensate for the change in sensor co-ordinate frame and dynamically transform applied forces with respect to the system base frame as given in Table 6 (in Appendix). A comparative study was conducted on the forces sensed by the FT sensor before and after applying the homogeneous transformation, comparing them with the actual force applied using a digital force gauge. Figures in Table 6 (in Appendix) depicts the comparison plots for FT sensor readings and force gauge readings before and after homogeneous transformation respectively for various standard orientations of control handle. The transformed force values were used by power assist algorithm to move system in intended direction.

3.2.3. Result and discussion for force transformation of intermediate orientations of control handle

The intermediate orientations were achieved by rotating control handle through θ_1=0˚, ±45˚ and θ_2=0˚, ±45˚ or both angles simultaneously. This causes changes in orientation of FT sensors (i.e., sensor co-ordinate frame) with respected to system base frame. Due to the change in orientation of FT sensor, the forces applied on control handle along system base frame were sensed along two or more directions of sensor co-ordinate frame. The developed homogeneous transformation algorithm transformed these multiple force components into single force component as discussed in Table 7 (in Appendix). A comparative study was conducted on the forces sensed by the FT sensor before and after applying the homogeneous transformation, comparing them with the actual force applied using a digital force gauge. Figures in Table 7 (in Appendix) depicts the comparison plots for FT sensor readings and force gauge readings before and after homogeneous transformation respectively for various intermediate orientations of control handle. The transformed force values were used by power assist algorithm to move system in intended direction. This provides an easy to operate system even if the control handle is rotated in intermediate orientations.

3.3. Summary of result and discussion

The control flexibility of power assisted ceiling suspended system depends on multiple factors like sensing technology used in FT sensor, the control handle design and ability to orient it in three-dimensional space. The homogeneous transformation technique used in this research paper allows the system to be controlled from multiple directions. Especially when control handle is rotated in standard and intermediate orientations, where force applied by the operator on control handle is sensed in multiple directions due to change in orientation of FT sensor. The developed homogeneous transformation algorithm transforms these multiple force components into single resultant force component, which can be effectively utilized by power assist algorithm to move system in intended direction of force applied by operator on the control handle. The results obtained after application of pull force along the system base frame are discussed in detail in Tables 5 to 7. Similar, discussion can be interpreted for push force along the system base frame based on the results shown in Tables 5 to 7. As per the existing requirement of power assist ceiling suspended system, only the forces were utilized for the movement of power assist ceiling suspended system in three-dimensional space. Therefore, the scope of the results obtained was kept limited to transformation of forces only. Future studies could explore a power-assist ceiling-suspended system using only torque control or a combination of force and torque control methods. In these cases, the homogeneous transformation of forces and torques could be further investigated.

3.4. Findings of the research work

The key finding is that the application of a homogeneous transformation matrix enables effective compensation for changes in the orientation of a multi-axis FT sensor, due to the rotation of a control handle in a power-assist ceiling-suspended system. This transformation matrix approach accurately adjusts the sensor readings to reflect true force values despite changes in handle orientation, thus solving the problem of mis-mapping of operator applied forces associated with rotation and enables seamless control in multiple directions regardless of the handle's orientation. The findings are summarized as follows:

a. Accurate orientation compensation
- The transformation matrix effectively compensates for errors caused by changes in the orientation of the control handle.
- Mapping of FT sensor readings remained accurate across various handle positions, essential for applications requiring precise force and torque measurements.

b. Reliable rotatable control handle performance
- The transformation matrix consistently reduced discrepancies in sensor readings during both experimental and real-time dynamic conditions.
- Experimental results confirmed that the approach improves rotatable control handle performance, making it suitable for environments where rotational adjustments are common.

c. Multi-directional control capability
- The system's control flexibility is enhanced by the transformation technique, allowing control from multiple directions based on handle orientation.
- This feature is valuable in industrial and robotic settings, where multi-directional manipulation of the control handle is frequently required.

d. Efficient force transformation
- When the control handle is rotated, the homogeneous matrix transforms complex directional force components into a single resultant force vector.
- This resultant force is effectively used by the power-assist algorithm, enabling the system to move precisely in the direction intended by the operator.

e. Improved system responsiveness
- By dynamically adjusting to the operator's input across different orientations, the system demonstrates enhanced responsiveness, accuracy.
- The homogeneous transformation matrix allows for seamless operation and reliable control, especially in applications where precise real-time adjustments are critical.

These findings collectively demonstrate the utility of the homogeneous transformation matrix in enhancing the accuracy and adaptability of FT sensor-based systems, making it a promising solution for various industrial applications.

4. CONCLUSION

The power assist ceiling suspended systems plays crucial role in reducing workers burden to operate high inertia machines. The power assist techniques using FT sensor as sensing element are under research and pose significant possibilities to improve human machine interactions. In this study, the challenge of compensating FT sensor orientation to enhance control flexibility of power assist ceiling suspended system was addressed. This research paper discussed the technique for transformation of FT sensor co-ordinate frame with respect to the system base frame using homogeneous transformation developed for existing rotatable control handle mechanism. The proposed technique helps to accurately read and dynamically transform the force values of FT sensor with respect to the system base frame for different orientations of rotatable control handle. The transformed values of forces are utilized by power assist algorithm to move the system in direction of force applied by user irrespective of control handle orientation. This adaptive technique provided seamless control of the power assist ceiling suspended system from any direction during handling and movement by simply rotating the control handle, thus enhancing user convenience and system flexibility.

This research paper presents both theoretical and experimental validation/evidences for its concluding findings. The theoretical evidence includes a detailed mathematical derivation of the homogeneous transformation matrix, while experimental validation is provided through controlled tests demonstrating the matrix's effectiveness in correcting orientation-related misalignment in FT sensor forces. The matrix accurately compensates for orientation discrepancies, producing force measurements that closely match the expected direction of operator-applied force. The developed algorithm consolidates multiple force components into a single resultant force. A comparative analysis was performed on the forces sensed by the FT sensor before and after applying the homogeneous transformation, with results compared against actual force values measured using a digital force gauge. These transformed force values are then utilized by the power-assist algorithm to guide the system in the intended direction, enabling intuitive control even when the handle is positioned in intermediate orientations.

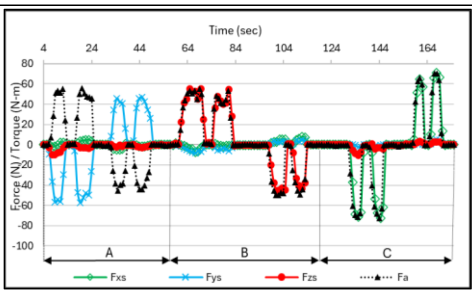
The findings presented in this research paper focused exclusively on the transformation of forces to meet the current needs of the power-assisted ceiling-suspended system. Future studies could explore only torque or a combination of force and torque transformation analysis to improve the upgraded multi degrees-of-freedom system's control capabilities. This would further enhance the system's adaptability and control capabilities, supporting a broader range of movements and adjustments. Additionally, integrating this technique with advanced algorithms could improve response times and overall efficiency, extending its utility to a wide array of dynamic environments in both research and industrial systems such as ceiling suspended systems.

The results of this research work hold substantial significance for the field of robotics, control systems, and broader applications involving FT sensors in variable orientations. The study addresses a fundamental challenge in sensor accuracy when devices are used in dynamic or rotated positions, providing a robust solution for compensating orientation-induced errors/mis-mapping of forces. This development enhances the precision and reliability of FT sensors in real-time applications, advancing the capabilities of robotic control and manipulation systems.

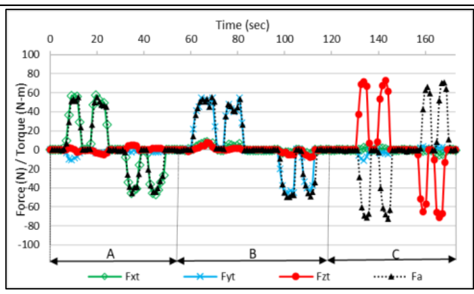
APPENDIX

Table 6. Comparison of FT sensor readings and force gauge readings before and after homogeneous transformation for standard orientations of the control handle

<table>
<tr><th>Sr. no.</th><th>Angles</th><th>Before homogeneous transformation</th><th>After homogeneous transformation</th></tr>
<tr><td>1.</td><td>θ_1=+90° and θ_2=0°</td><td>



A. F_a force applied in x direction along the system base frame is sensed by $-F_{ys}$ component of the sensor co-ordinate frame.
B. F_a force applied in y direction along the system base frame is sensed by F_{zs} component of the sensor co-ordinate frame.
C. F_a force applied in z direction along the system base frame is sensed by F_{xs} component of the sensor co-ordinate frame.
</td><td>



A. F_a force applied in x direction of the system base frame is transformed from $-F_{ys}$ component into F_{xt} along the system base frame.
B. Fa force applied in y direction of the system base frame is transformed from F_{zs} component into Fyt along the system base frame.
C. Fa force applied in z direction of the system base frame is transformed from F_{xs} into$-F_{zt}$ along the system base frame.
</td></tr>
</table>

Table 6. Comparison of FT sensor readings and force gauge readings before and after homogeneous transformation for standard orientations of the control handle *(continued)*

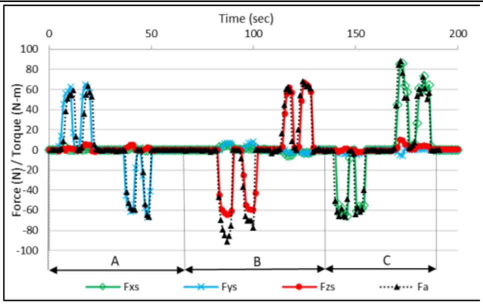
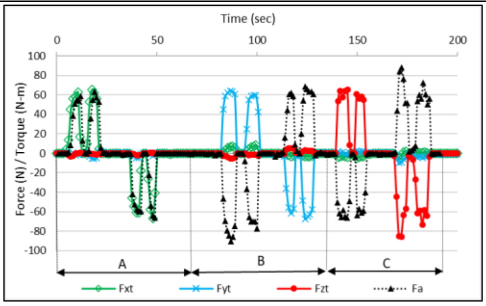
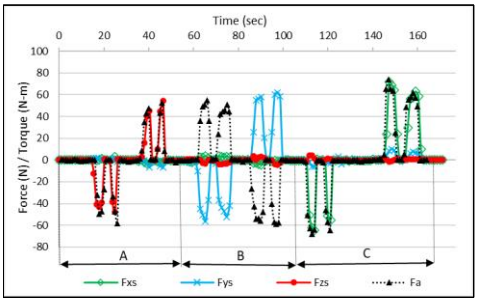
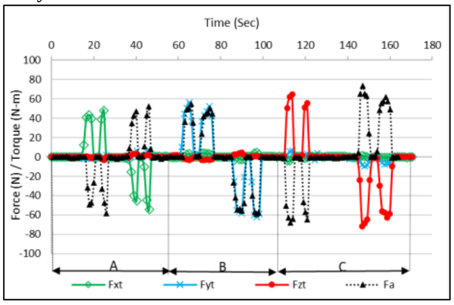
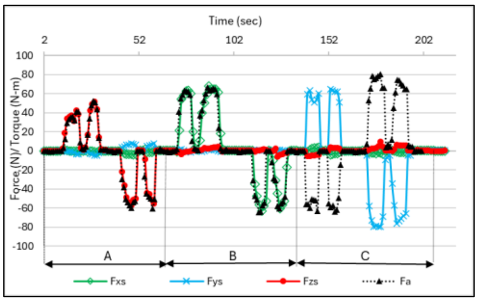
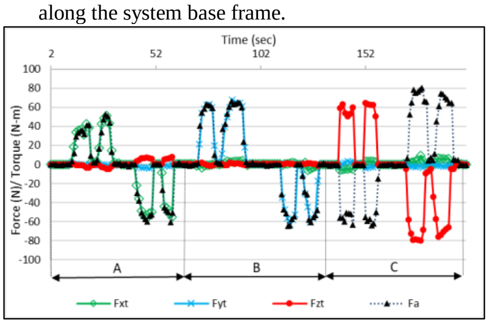
Sr. no.	Angles	Before homogeneous transformation	After homogeneous transformation
2.	θ_1=-90° and θ_2=0°	 A. F_a force applied in x direction along the system base frame is sensed by F_{ys} component of the sensor co-ordinate frame. B. F_a force applied in y direction along the system base frame is sensed by F_{zs} component of the sensor co-ordinate frame. C. F_a force applied in z direction along the system base frame is sensed by F_{xs} component of the sensor co-ordinate frame.	 A. F_a force applied in x direction of the system base frame is transformed from F_{ys} component into F_{xt} along the system base frame. B. F_a force applied in y direction of the system base frame is transformed from F_{zs} component into $-F_{yt}$ along the system base frame. C. F_a force applied in z direction of the system base frame is transformed from F_{xs} into $-F_{zt}$ along the system base frame.
3.	θ_1=+180° and θ_2=0°	 A. F_a force applied in x direction along the system base frame is sensed by F_{zs} component of the sensor co-ordinate frame. B. F_a force applied in y direction along the system base frame is sensed by $-F_{ys}$ component of the sensor co-ordinate frame. C. F_a force applied in z direction along the system base frame is sensed by F_{xs} component of the sensor co-ordinate frame.	 A. F_a force applied in x direction of the system base frame is transformed from F_{zs} component into $-F_{xt}$ along the system base frame. B. F_a force applied in y direction of the system base frame is transformed from $-F_{ys}$ component into F_{yt} along the system base frame. C. F_a force applied in z direction of the system base frame is transformed from F_{xs} component into $-F_{zt}$ along the system base frame.
4.	θ_1=0° and θ_2=+90°	 A. F_a force applied in x direction along the system base frame is sensed by F_{zs} component of the sensor co-ordinate frame. B. F_a force applied in y direction along the system base frame is sensed by F_{xs} component of the sensor co-ordinate frame. C. F_a force applied in z direction along the system base frame is sensed by $-F_{ys}$ component of the sensor co-ordinate frame.	 A. F_a force applied in x direction of the system base frame is transformed from F_{zs} into F_{xt} along the system base frame. B. F_a force applied in y direction of the system base frame is transformed from F_{xs} into F_{yt} along the system base frame. C. F_a force applied in z direction of the system base frame is transformed from $-F_{ys}$ into $-F_{zt}$ along the system base frame.

Table 6. Comparison of FT sensor readings and force gauge readings before and after homogeneous transformation for standard orientations of the control handle *(continued)*

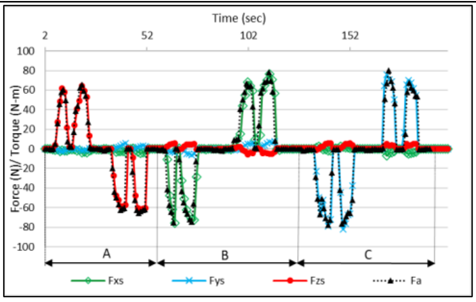
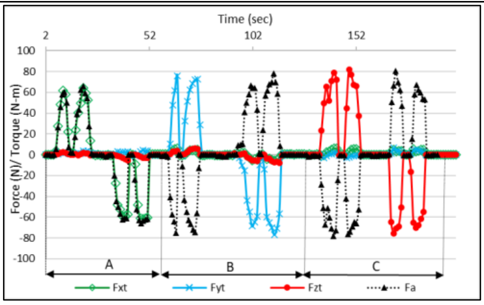
Sr. no.	Angles	Before homogeneous transformation	After homogeneous transformation
5.	θ_1=0˚ and θ_2=–90˚	 A. F_a force applied in x direction along the system base frame is sensed by F_{zs} component of the sensor co-ordinate frame. B. F_a force applied in y direction along the system base frame is sensed by F_{xs} component of the sensor co-ordinate frame. C. F_a force applied in z direction along the system base frame is sensed by F_{ys} component of the sensor co-ordinate frame.	 A. F_a force applied in x direction of the system base frame is transformed from F_{zs} into F_{xt} along the system base frame. B. F_a force applied in y direction of the system base frame is transformed from F_{xs} into $-F_{yt}$ along the system base frame. C. F_a force applied in z direction of the system base frame is transformed from F_{ys} into $-F_{zt}$ along the system base frame.

Table 7. Comparison of FT sensor readings and force gauge readings before and after homogeneous transformation for intermediate orientations of the control handle

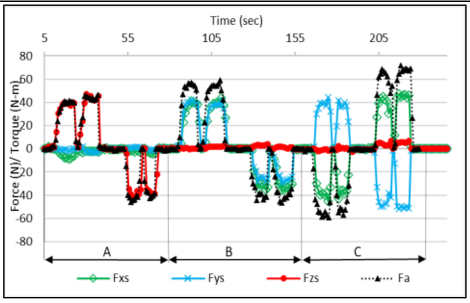
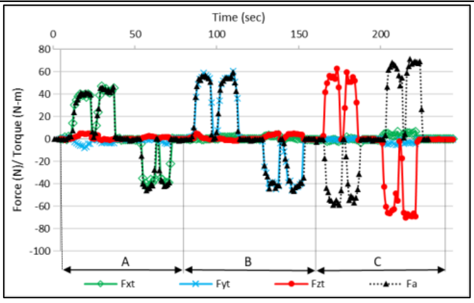
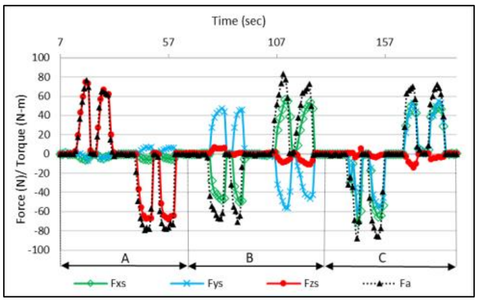
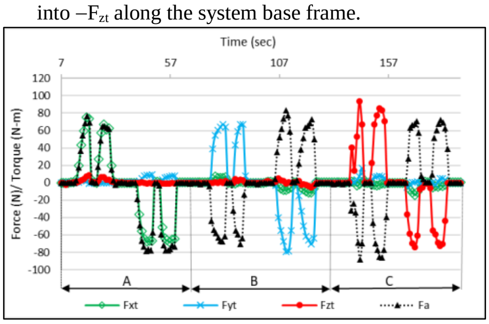
Sr. no.	Angles	Before homogeneous transformation	After homogeneous transformation
1.	θ_1=0˚ and θ_2=+45˚	 A. F_a force applied in x direction along the system base frame is sensed by F_{zs} component of the sensor co-ordinate frame. B. F_a force applied in y direction along the system base frame is sensed by F_{xs} and F_{ys} components of sensor co-ordinate frame. C. F_a force applied in z direction along the system base frame is sensed by -F_{xs} and F_{ys} components of sensor co-ordinate frame.	 A. F_a force applied in x direction of the system base frame is transformed from F_{zs} into F_{xt} along the system base frame. B. F_a force applied in y direction of the system base frame is transformed from F_{xs} and F_{ys} components into F_{yt} along the system base frame. C. F_a force applied in z direction of the system base frame is transformed from -F_{xs} and F_{ys} components into $-F_{zt}$ along the system base frame.
2.	θ_1=0˚ and θ_2=– 45˚	 A. F_a force applied in x direction along the system base frame is sensed by F_{zs} component of the sensor co-ordinate frame.	 A. F_a force applied in x direction of the system base frame is transformed from F_{zs} into F_{xt} along the system base frame.

Table 7. Comparison of FT sensor readings and force gauge readings before and after homogeneous transformation for intermediate orientations of the control handle *(continued)*

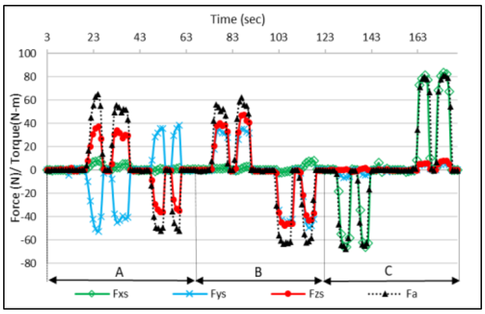
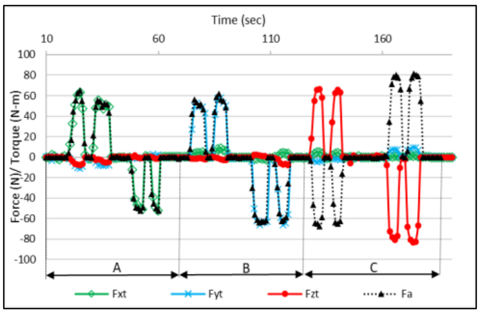
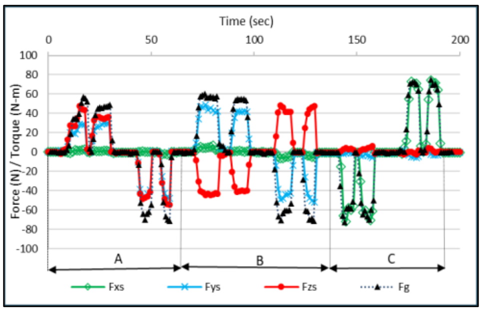
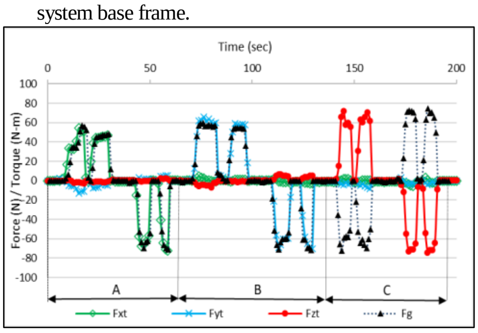
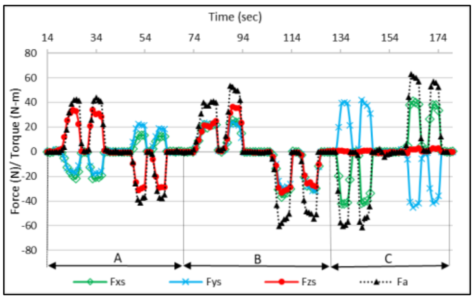
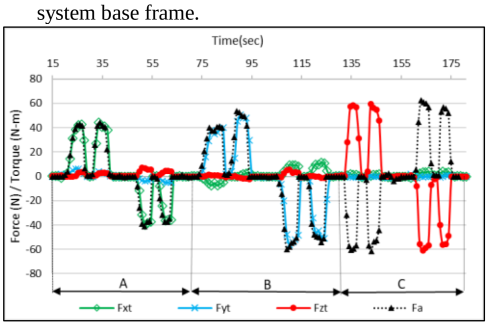
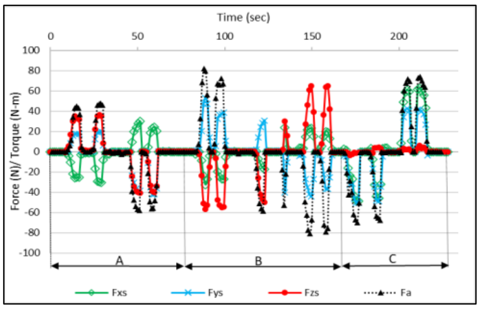
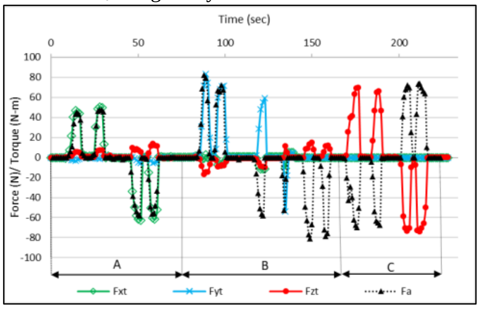
Sr. no.	Angles	Before homogeneous transformation	After homogeneous transformation
2.	θ_1=0° and θ_2=–45°	B. F_a force applied in y direction along the system base frame is sensed by F_{xs} and $-F_{ys}$ components of sensor co-ordinate frame. C. F_a force applied in z direction along the system base frame is sensed by F_{xs} and F_{ys} components of sensor co-ordinate frame.	B. F_a force applied in y direction of the system base frame is transformed from F_{xs} and $-F_{ys}$ components into $-F_{yt}$ along the system base frame. C. F_a force applied in z direction of the system base frame is transformed from $-F_{xs}$ and F_{ys} components into $-F_{zt}$ along the system base frame.
3.	θ_1=+45° and θ_2=0°	 A. F_a force applied in x direction along the system base frame is sensed by F_{zs} and $-F_{ys}$ components of sensor co-ordinate frame. B. F_a force applied in y direction along the system base frame is sensed by F_{zs} and F_{ys} components of sensor co-ordinate frame. C. F_a force applied in z direction along the system base frame is sensed by F_{xs} components of sensor co-ordinate frame.	 A. F_a force applied in x direction of the system base frame is transformed from F_{zs} and $-F_{ys}$ components into F_{xt} along the system base frame. B. F_a force applied in y direction of the system base frame is transformed from F_{zs} and F_{ys} components into F_{yt} along the system base frame. C. F_a force applied in z direction of the system base frame is transformed from F_{xs} into $-F_{zt}$ along the system base frame.
4.	θ_1=–45° and θ_2=0°	 A. F_a force applied in x direction along the system base frame is sensed by F_{ys} and F_{zs} component of the sensor co-ordinate frame. B. F_a force applied in y direction along the system base frame is sensed by $-F_{zs}$ and F_{ys} component of the sensor co-ordinate frame. C. F_a force applied in z direction along the system base frame is sensed by F_{xs} component of the sensor co-ordinate frame.	 A. F_a force applied in x direction of the system base frame is transformed from F_{ys} and F_{zs} component into F_{xt} along the system base frame. B. F_a force applied in y direction of the system base frame is transformed from $-F_{zs}$ and F_{ys} component into F_{yt} along the system base frame. C. F_a force applied in z direction of the system base frame is transformed from F_{xs} into $-F_{zt}$ along the system base frame.
5.	θ_1=+45° and θ_2=+45°	 A. F_a force applied in x direction along the system base frame is sensed by $-F_{xs}$, $-F_{ys}$, and F_{zs} components of sensor co-ordinate frame.	 A. F_a force applied in x direction of the system base frame is transformed from $-F_{xs}$, $-F_{ys}$, and F_{zs} components into F_{xt} along the system base frame.

Table 7. Comparison of FT sensor readings and force gauge readings before and after homogeneous transformation for intermediate orientations of the control handle *(continued)*

Sr. no.	Angles	Before homogeneous transformation	After homogeneous transformation
5.	θ_1=+45° and θ_2=+45°	B. F_a force applied in y direction along the system base frame is sensed by F_{xs}, F_{ys}, and F_{zs} components of sensor co-ordinate frame. C. F_a force applied in z direction along the system base frame is sensed by $-F_{ys}$ and F_{xs} components of sensor co-ordinate frame.	B. F_a force applied in y direction of the system base frame is transformed from F_{xs}, F_{ys}, and F_{zs} into F_{yt} along the system base frame. C. F_a force applied in z direction of the system base frame is transformed from $-F_{ys}$ and F_{xs} component into $-F_{zt}$ along the system base frame.
6.	θ_1=−45° and θ_2=−45°	 A. F_a force applied in x direction along the system base frame is sensed by $-F_{xs}$, F_{ys}, and F_{zs} components of sensor co-ordinate frame. B. F_a force applied in y direction along the system base frame is sensed by $-F_{xs}$, F_{ys}, and $-F_{zs}$ components of sensor co-ordinate frame. C. F_a force applied in z direction along the system base frame is sensed by F_{xs} and F_{ys} components of sensor co-ordinate frame.	 A. F_a force applied in x direction of the system base frame is transformed from $-F_{xs}$, F_{ys}, and F_{zs} components into F_{xt} along the system base frame. B. F_a force applied in y direction of the system base frame is transformed from $-F_{xs}$, F_{ys}, and $-F_{zs}$ components into F_{yt} along the system base frame. C. F_a force applied in z direction of the system base frame is transformed from F_{xs} and F_{ys} components into $-F_{zt}$ along the system base frame.

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BIOGRAPHIES OF AUTHORS

Shivam Suresh Zagade is currently pursuing Master of Technology in Mechatronics at the Department of Manufacturing Engineering and Industrial Management of COEP Technological University (COEP Tech), Pune (Formerly College of Engineering Pune (COEP)), Maharashtra, India. He has completed a Diploma in Mechanical Engineering from Government Polytechnic Pune (An Autonomous Institute of Government of Maharashtra). He has received a Bachelor of Engineering degree in Mechanical Engineering from Government College of Engineering and Research, Avasari, Pune affiliated to the Savitribai Phule Pune University (SPPU), Maharashtra, India. His area of interest is mechatronics, robotics, and automation. He can be contacted at email: shivamzagade2@gmail.com, or zagadess22.mfg@coeptech.ac.in.

Rajiv Basavarajappa is currently working as Associate Professor, Department of Production Engineering and Industrial Management, COEP Technological University (Formerly, College of Engineering, Pune). He obtained his Ph.D. in 2008 respectively from College of Engineering, Pune (COEP). He has more than 21 years of experience in teaching/industry and research. He has published more than 110 papers, guided 7 Ph.D. students and 70 M.Tech. students. His area of research is operations research, metal cutting, reliability engineering, laser cutting, and EDM, and mechatronics. He can be contacted at email: rbh.mfg@coeptech.ac.in.

Sudhir Madhav Patil is currently working as Associate Professor in the Department of Manufacturing Engineering and Industrial Management of COEP Technological University (COEP Tech), Pune (Formerly College of Engineering Pune (COEP)), Maharashtra, India. He received Bachelor of Engineering degree in Mechanical Engineering from the North Maharashtra University, Maharashtra, India and Master and Ph.D. degree in Production Engineering from the Savitribai Phule Pune University (SPPU), Maharashtra, India. He is a Member of The Institution of Engineers (India) and a Life Member of Tribology Society of India (LMTSI). His main research interest includes mechatronics, manufacturing automation, robotics and AI, tribology, and supply chain management. He has published several research papers and is a co-inventor for couple of Indian patents. He can be contacted at email: smp.prod@coeptech.ac.in, sudhir.smp@gmail.com, or smp.mfg@coeptech.ac.in.

Abhishek Pradeep Buzruk is currently working as mechanical architect at Philips India Limited, Pune, Maharashtra, India. He received Bachelor of Engineering degree in Mechanical Engineering from Savitribai Phule Pune University (SPPU), Maharashtra, India and Master of Engineering from NTTF (Nettur Technical Training Foundation), Bangalore, Karnataka, India. His areas of interest are medical devices, system design, mechatronics hardware development, lifecycle management, and new product development. He can be contacted at email: abhishekpb@gmail.com.

Kshitij Ghanshyam Jiwane is currently working as Mechatronics Engineer at Philips India Limited, Pune, Maharashtra, India. He received Bachelor of Engineering degree in Electronics Engineering from All India Shri Shivaji Memorial Society's Institute of Information Technology, Pune, affiliated to the Savitribai Phule Pune University (SPPU), Maharashtra, India and Master of Technology in mechatronics from COEP Technological University (COEP Tech), Pune (Formerly College of Engineering Pune (COEP)) Maharashtra, India. His areas of interest are mechatronics and embedded electronics. He can be contacted at email: kshitij.gj@gmail.com.

Tole Sutikno is a lecturer in the Master Program of Electrical Engineering, Faculty of Industrial Technology, Universitas Ahmad Dahlan, Indonesia. He received his B.Eng., M.Eng., and Ph.D. degrees in Electrical Engineering from Universitas Diponegoro, Universitas Gadjah Mada, and Universiti Teknologi Malaysia in 1999, 2004, and 2016, respectively. Since July 2023, he has been a Professor at UAD in Yogyakarta, Indonesia, and previously an associate professor since June 2008. According to Stanford University and Elsevier, he has been ranked among the top 2% of scientists in the world since 2021. He is currently the Editor-in-Chief of TELKOMNIKA and the Head of the Embedded Systems and Power Electronics Research Group (ESPERG). His research interests include the fields of digital design, industrial applications, industrial electronics, industrial informatics, power electronics, motor drives, renewable energy, FPGA applications, embedded systems, artificial intelligence, intelligent control, information technology, and digital libraries. He can be contacted at email: tole@te.uad.ac.id or tole@ee.uad.ac.id.