Fakher Chaari, National School of Engineers, University of Sfax, Sfax, Tunisia
Mohamed Haddar, National School of Engineers of Sfax (ENIS), Sfax, Tunisia
Young W. Kwon, Department of Manufacturing Engineering and Aerospace Engineering, Graduate School of Engineering and Applied Science, Monterey, CA, USA
Francesco Gherardini, Dipartimento Di Ingegneria, Edificio 25, Università Di Modena E Reggio Emilia, Modena, Modena, Italy
Vitalii Ivanov, Department of Manufacturing Engineering Machine and Tools, Sumy State University, Sumy, Ukraine
Lecture Notes in Mechanical Engineering (LNME) publishes the latest developments in Mechanical Engineering - quickly, informally and with high quality. Original research reported in proceedings and post-proceedings represents the core of LNME. Volumes published in LNME embrace all aspects, subfields and new challenges of mechanical engineering. Topics in the series include:

- Engineering Design
- Machinery and Machine Elements
- Mechanical Structures and Stress Analysis
- Automotive Engineering
- Engine Technology
- Aerospace Technology and Astronautics
- Nanotechnology and Microengineering
- Control, Robotics, Mechatronics
- MEMS
- Theoretical and Applied Mechanics
- Dynamical Systems, Control
- Fluid Mechanics
- Engineering Thermodynamics, Heat and Mass Transfer
- Manufacturing
- Precision Engineering, Instrumentation, Measurement
- Materials Engineering
- Tribology and Surface Technology

To submit a proposal or request further information, please contact the Springer Editor of your country:

- Dr. Mengchu Huang at mengchu.huang@springer.com
- Priya Vyas at priya.vyas@springer.com
- Swati Meherishi at swati.meherishi@springer.com
- Dr. Leontina Di Cecco at Leontina.dicecco@springer.com

To submit a proposal for a monograph, please check our Springer Tracts in Mechanical Engineering at [http://www.springer.com/series/11693](http://www.springer.com/series/11693) or contact Leontina.dicecco@springer.com

More information about this series at [http://www.springer.com/series/11236](http://www.springer.com/series/11236)
Advances in Mechanical Engineering

Select Proceedings of ICAME 2020
It is our pleasure and honour to bring you these findings of research and innovation from the International Conference on Advances in Mechanical Engineering (ICAME 2020) held on 10 and 11 January 2020 organized by the Department of Mechanical Engineering, Visvesvaraya National Institute of Technology, Nagpur, India. This conference was the beginning of a year-long Diamond Jubilee year celebrations of VNIT Nagpur’s foundation day. ICAME 2020 provided an international forum where researchers, academicians and scientists from interdisciplinary fields presented their synergistic solutions to frontier issues of mechanical engineering.

We received around 200 research manuscripts from various domains like thermal engineering, CFD, machine design, sustainability, IoT, robotics, manufacturing engineering, biomechanics, machine learning, machine vision, optimization, industrial engineering and many other allied domains. During 12 technical sessions spread over two days, the conference witnessed the presentations by participants from different NITs, IITs and universities in India as well as abroad. Out of 200 plus received papers, only 101 manuscripts are accepted for inclusion in this proceedings. The keynote talks, technical sessions and panel discussions of the conference were focused on holistic contributions of mechanical engineering concerning the society in general and industry in particular.

We are highly grateful to the authors for their contributions and all the expert reviewers for their valuable advice. We take this opportunity to thank the members of the organizing committees for their unwavering commitment.

We are indebted to TEQIP-III, MSME-DI Nagpur, DST-SERB New Delhi, MOIL Nagpur, SBI VRCE Branch Nagpur and many other industries, establishments and agencies in India for their generous sponsorship and support for the conference.
We extend our heartfelt gratitude to Springer Nature for its professional assistance and particularly Mr. Akash Chakraborty and Ms. Rini Christy who supported this publication.

Nagpur, India
Presov, Slovakia

Prof. Vilas R. Kalamkar
Prof. Katarina Monkova
Dual Quaternion-Based Kinematic Modelling of Serial Manipulators

Mohsin Dalvi, Shital S. Chiddarwar, Saumya Ranjan Sahoo, and M. R. Rahul

Performance Analysis of Corrugated Inclined Basin Solar Distillation System Coupled with Parabolic Trough Collector

Sandeep Joshi, Shubham Tagde, Aboli Pingle, Nikhil Bhave, and Tushar Sathe

Mechanical Design of Omnidirectional Spherical Wall Traversing Robot

Yogesh Phalak, Rajeshree Deotalu, Onkar, and Sapan Agrawal

Fabrication and Performance Analysis of a Device to Transform Vibration Energy on an Automobile

Dheeraj H. Bonde, Nitin K. Panche, Hrishikesh S. Meshram, Vrushabh W. Dhongade, Atul V. Dharmik, Jayesh D. Parate, Mangesh G. Pardhi, and Vinit S. Gupta

Robust Backstepping Controller for an Omniwheeled Mobile Robot with Uncertainties and External Disturbances

Zeeshan Ul Islam, Saumya Ranjan Sahoo, Mohammad Saad, Uddesh Tople, and Amrapali Khandare

Micro-mechanical Analyses of Particle Reinforced ex situ Bulk Metallic Glass Matrix Composites

S. Gouripriya and Parag Tandaiya

Life Estimation of Circumferentially Notch Round Bars Using J Integral

Richa Agrawal, Rashmi Uddanwadiker, and Pramod M. Padole
Sushmita Deka, Ramesh Babu Pallekonda, and Maneswar Rahang

Sameer Raj Singh and Ashish B. Deoghare

Bhushan Y. Dharmik and Nitin K. Lautre

P. P. Shirpurkar, V. M. Sonde, P. T. Date, and T. R. Badule

Ashish Kumar, Anupam Das, and Swarnambuj Suman

Nisha Gupta, Avanish Kumar Dubey, and Dhruv Kant Rahi

Sushant Satputaley, Karan Ksheersagar, Bijay Sankhari, Rahul Kavishwar, and Kshitij Waghdhare

Sumit S. Khune and Amit R. Bhende

Pooja Jhunjhunwala, Pramod M. Padole, and S. B. Thombre

Smit V. Motghare

Ranjan Singh, Virendra Singh, and T. V. K. Gupta

Sanjay S. Toshniwal and Raghu V. Prakash

Chinmay M. Salkar, Gaurao J. Tapare, Mayank A. Murkute, Chetan R. Zingre, Hansraj A. Mohod, and Vinit S. Gupta
<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparative Study of Nano-finishing of Si (100) Using DDMAF and Allied Processes</td>
<td>377</td>
</tr>
<tr>
<td>Kheelraj Pandey, Ajendra Kumar Singh, and Gaurav Raj Pandey</td>
<td></td>
</tr>
<tr>
<td>Optimization of Thickness of Hollow Punch-Die for Proposed Solar-Assisted Leaf Plate and Cup Making Machine</td>
<td>385</td>
</tr>
<tr>
<td>Abhay Nilawar, Pravin Potdukhe, and Deepak V. Bhole</td>
<td></td>
</tr>
<tr>
<td>Development of Briquette Cum Pellet Making Machine</td>
<td>391</td>
</tr>
<tr>
<td>Yeshwant M. Sonkhaskar, Gajanan R. Nikhade, Saket Dharmik, Utkarsh Deshmukh, and Pramod Dhote</td>
<td></td>
</tr>
<tr>
<td>Towards the Development of Low-Cost Vacuum Setup for Customized Implant Manufacturing</td>
<td>399</td>
</tr>
<tr>
<td>Sanjay Randiwe, Dheeraj Bhiogade, and Abhaykumar M. Kuthe</td>
<td></td>
</tr>
<tr>
<td>Simulation Study on Effect of Variable Curvature on the Modal Properties of Curved Cantilever Beams</td>
<td>407</td>
</tr>
<tr>
<td>Aqleem Siddiqui, Girish Dalvi, Akshay Patil, and Surabhi Chavan</td>
<td></td>
</tr>
<tr>
<td>Variation in the Properties of Spot Weldments of Cold Rolled Mild Steel Welded with Filler Metal by Annealing Treatment</td>
<td>415</td>
</tr>
<tr>
<td>Sushil T. Ambadkar and Deepak V. Bhole</td>
<td></td>
</tr>
<tr>
<td>Effect of Moisture Content and Fiber Orientation on the Mechanical Behavior of GFRP Composites</td>
<td>425</td>
</tr>
<tr>
<td>Alok Behera, M. M. Thawre, Atul Ballal, Prathamesh Babrekar, Pratik Vaidya, Satya Vijetha, and Tushar Sawant</td>
<td></td>
</tr>
<tr>
<td>Experimental Investigation and Simulation of Modified Evaporative Cooling System</td>
<td>433</td>
</tr>
<tr>
<td>Manju Lata and Dileep Kumar Gupta</td>
<td></td>
</tr>
<tr>
<td>Study and Analysis of Various Parameters of Bio-mechanization Plant</td>
<td>437</td>
</tr>
<tr>
<td>Deepak Patil, Rahul Barjibhe, Lakhman Meghani, Omkar Nanaware, Tejas More, and Aditya Pujari</td>
<td></td>
</tr>
<tr>
<td>Robust Sliding Mode Controller (RSMC) for an Omniwheeled Mobile Robot with Uncertainties and External Perturbations</td>
<td>441</td>
</tr>
<tr>
<td>Mohammad Saad, Uddesh Tople, Amrapali Khandare, and Zeeshan U Islam</td>
<td></td>
</tr>
</tbody>
</table>
Ranjit J. Singh and Trushar B. Gohil

Alex Sherjy Syriac and M. R. Rahul

Sagar Dave, Sirshendu Chattopadhyay, and Deepak Gupta

Someshwar S. Bhakre and Pravin D. Sawarkar

Tushar Sathe, A. S. Dhoble, Sandeep Joshi, C. Mangrulkar, and V. G. Choudhari

Shawli Bardhan and Sukanta Roga

V. Sri Pavan RaviChand, Anoop Kumar Srivastava, Abhishek Kumar, H. N. Suresha Kumar, and K. A. Keshavamurthy

N. N. Sirdesai, A. Aravind, and S. Panchal

Pranjali S. Deole and Priya M. Khandekar

Nikhil Khaire, Vivek Bhure, and Gaurav Tiwari

Vivek Patel, Sanket Suresh Kalantre, Gaurav Tiwari, and Ravikumar Dumpala

Rohini Y. Bhute and M. R. Rahul
Dr. Vilas R. Kalamkar is a professor and head of mechanical engineering department of Visvesvaraya National Institute of Technology, Nagpur, India. He received his PhD in aerodynamics from the Indian Institute of Technology Bombay. His areas of research are CFD and turbo machinery. He has more than 20 years of teaching experience. Apart from several research articles in journals and conference proceedings, he has also filed 2 patents. He has undertaken 4 research projects and many consultancy projects. He was invited to deliver keynote lectures at various international conferences in places like Korea, Malaysia and Dubai. He was conferred with the best teacher award, research fellowships and best paper award for his contribution in teaching and research.

Dr. Katarina Monkova is a full professor of Faculty of Manufacturing Technologies with the seat in Presov, Slovakia. She is a scientific researcher at technical university with pedagogical activities like computer-aided technical devices design, analysis and simulation, cellular material. She has done PhD in manufacturing technologies and metallurgy. She has more than 300 publications with 20 invited presentations at international conferences. She is also a leader of 7 national scientific-research projects and 1 international project and member of more than 20 national projects with educational and scientific grants. She is a recipient of various awards like Rector’s award and Dean’s Award.
Dual Quaternion-Based Kinematic Modelling of Serial Manipulators

Mohsin Dalvi, Shital S. Chiddarwar, Saumya Ranjan Sahoo, and M. R. Rahul

Abstract In this paper, a dual quaternion-based methodology for computing the forward and inverse kinematic models for a serial manipulator is presented. A dual quaternion-based forward kinematics model is developed for the Kuka LBR iiwa 7 R800 cobot. An inverse kinematics model is developed that uses dual quaternion differential kinematics and includes Jacobian transpose and damped least squares methods for determining Jacobian pseudo-inverse. Implementation of these methods on a given trajectory shows that, compared to damped least squares, the Jacobian transpose method is faster, but is less immune to singularity and gives more jerky motions.

Keywords Cobot · Dual quaternions · Differential motion operator · Jacobian transpose · Damped least squares

1 Introduction

During robot programming, the orientation and position of robot end-effector must change as smoothly as a human hand. Quaternions, initially developed as a generalization of complex numbers for three dimensions, are robust than the popularly used Euler angles and rotation matrices for representing orientations. They are compact, computationally efficient, immune to gimbal lock and mathematical singularities, and also provide natural orientation interpolation [1]. However, using vectors and quaternions for representing simultaneous translations and rotations leads to inconsistencies [2].

A dual quaternion (DQ) uses dual numbers to unify rotations and translations into a single state instead of defining separate vectors for them [3]. DQs have been used for kinematic modelling and pose control of serial manipulators [4, 5].
available literature on modelling with quaternions and DQs shows that there are ambiguities in representation (Hamiltonian and NASA-JPL), handedness (right and left) and reference frames (global and body) [6].

Differential kinematics is a widely used approach for inverse kinematics (IK) modelling. DQ and Plucker coordinates have been used to derive the geometrical Jacobian for serial manipulators [7]. DQs and quaternion exponential maps have been used to solve IK problems by considering joint limits [8]. Unlike the DQ differential operator, dealing with Jacobian matrix is well discussed in the literature.

The flow of the paper is as follows: Sect. 2 introduces dual quaternions, which is used in Sect. 3 to develop the forward and inverse kinematic models for a serial manipulator. The approach is applied for Kuka LBR IIWA 7 R800 cobot in Sect. 4. The results are discussed in Sect. 5, followed by conclusion in Sect. 6.

2 Mathematical Preliminaries

In this work, quaternions use Hamiltonian representation in right-handed coordinates. A quaternion is represented as \( q = [p_0, \mathbf{p}] = p_0 + p_1i + p_2j + p_3k \), where \( p \in \mathbb{H} \), \( p_0 \in \mathbb{R} \) is a scalar and \( \mathbf{p} = (p_1, p_2, p_3) \in \mathbb{R}^3 \) is a vector. The orthogonal unit vectors \( i, j, k \) satisfy the quaternion property \( i^2 = j^2 = k^2 = ijk = -1 \). This property is used to define quaternion algebra. Addition and multiplication are given by \( p + q = [p_0 + q_0, \mathbf{p} + \mathbf{q}] \) and \( p \otimes q = [p_0q_0 - \mathbf{p} \cdot \mathbf{q}, p_0\mathbf{q} + q_0\mathbf{p} + \mathbf{p} \times \mathbf{q}] \), respectively. Multiplication is non-commutative, but follows distributive and associative properties. The multiplicative inverse is given by \( p^{-1} = p^* / \|p\|^2 \), where \( p^* \) is the conjugate, defined as \( p^* = [p_0, -\mathbf{p}] \), and \( \|p\| \) is the norm, given by \( \|p\| = \sqrt{p \otimes p^*} = \sqrt{p_0^2 + \mathbf{p} \cdot \mathbf{p}} \). The identity quaternion is \( 1 = [1, \mathbf{0}] \).

A dual number has the form \( a = a_r + \epsilon a_d \), where \( a \in \mathbb{D} \), \( a_r \in \mathbb{R} \) is the real part, \( a_d \in \mathbb{R} \) is the dual part. The dual unit \( \epsilon \), satisfying \( \epsilon \neq 0 \), \( \epsilon^2 = 0 \) is used to define dual number algebra. Higher-order terms get removed during Taylor series expansion of dual function about real part to give \( f(a + \epsilon b) = f(a) + \epsilon b f'(a) \). This gives relations such as \( \cos(a + \epsilon b) = \cos a - \epsilon b \sin a \), and \( \sqrt{a + \epsilon b} = \sqrt{a} - \epsilon b / 2\sqrt{a} \).

A dual quaternion is written as \( \overline{p} = p_r + \epsilon p_d \), where \( p_r, p_d \in \mathbb{H} \) and \( \overline{p} \in \mathbb{DH} \). Addition and multiplication are given by \( p + q = (p_r + q_r) + \epsilon (p_d + q_d) \) and \( p \otimes q = p_r \otimes q_r + \epsilon (p_r \otimes q_d + p_d \otimes q_r) \), respectively. A DQ has three conjugates, namely dual conjugate \( \overline{p} = p_r - \epsilon p_d \), quaternion conjugate \( p^* = p_r^* + \epsilon p_d^* \), and dual quaternion conjugate \( \overline{p^*} = p_r^* - \epsilon p_d^* \). The identity DQ is \( 1 = [1, \mathbf{0}] + \epsilon [0, \mathbf{0}] \). The inverse DQ is \( 1 = [1, \mathbf{0}] + \epsilon [0, \mathbf{0}] \). The inverse DQ exists if \( p_r \neq 0 \). The DQ norm is obtained from \( \|p\| = \sqrt{p \otimes p^*} = \sqrt{\|p_r\|^2 + \epsilon 2[p_r p_d 0 + p_r \cdot p_d, 0]} \). If \( \|p_r\| = 1 \) and \( p_r p_d 0 + p_r \cdot p_d = 0 \), then \( \overline{p} \) is a unit DQ.
3 Kinematic Modelling of Serial Manipulator

The unit quaternion $\hat{r} = [\cos \frac{\theta}{2}, \hat{u} \sin \frac{\theta}{2}]$ represents rotation by angle $\theta$ about unit vector $\hat{u}$. The quaternion $t = [0, t]$ depicts translation $t = (t_x, t_y, t_z)$. Then, the composite transformation of rotation $\hat{r}$ followed by translation $t$ is given by the unit DQ

$$p = t \otimes \hat{r} = (1 + \epsilon \frac{1}{2} t) \otimes (\hat{r} + \epsilon 0) = \hat{r} + \epsilon \frac{1}{2} t \otimes \hat{r} = \left[ \cos \frac{\theta}{2}, \sin \frac{\theta}{2} \hat{u} \right] + \epsilon \frac{1}{2} \left[ -\sin \frac{\theta}{2} (t \cdot \hat{u}), \cos \frac{\theta}{2} t + \sin \frac{\theta}{2} (t \times \hat{u}) \right] \quad (1)$$

For a given unit DQ $p = p_r + \epsilon p_d$, quaternions $\hat{r}$ and $t$ are obtained using $\hat{r} = p_r$ and $t = 2 p_d \otimes p_d^* = 2 p_d \otimes \hat{r}^*$. For rotational quaternion $\hat{r} = [r_0, r]$, rotation parameters $\theta$ and $\hat{u}$ are obtained as $\theta = 2 \cos^{-1}(r_0)$ and $\hat{u} = r / \sin \frac{\theta}{2}$. When a vector $v_0$ is subjected to transformation $p$, the new vector $v_1$ is obtained from $v_1 = [1, 0] + \epsilon [0, v_1] = p \otimes ([1, 0] + \epsilon [0, v_0]) \otimes \hat{r}^*$.

3.1 Forward Kinematics (FK) Modelling

A link $i$ of a serial manipulator as seen in Fig. 1 has frames $\{i-1\}$ and $\{i\}$ attached to joints $i$ and $i+1$ present at its ends by following DH notations [9]. In order to coincide frame $\{i-1\}$ with frame $\{i\}$, an intermediate frame $\{i'\}$ is defined at intersection of $Z_{i-1}$ and $X_i$ axes. Then, using Eq. 1, screw transforms $q_i^Z = [\cos \frac{\theta_i}{2}, 0, 0, \sin \frac{\theta_i}{2}] + \epsilon \left[ -\frac{d_i}{2} \sin \frac{\theta_i}{2}, 0, 0, \frac{d_i}{2} \cos \frac{\theta_i}{2} \right]$ about $Z_{i-1}$ axis and $q_i^X = [\cos \frac{\theta_i}{2}, \sin \frac{\theta_i}{2}, 0, 0] + \epsilon \left[ -\frac{d_i}{2} \sin \frac{\theta_i}{2}, \cos \frac{\theta_i}{2}, 0, 0 \right]$ about $X_i$ axes are carried out. Let $C_\theta = \cos \frac{\theta_i}{2}$, $S_\theta = \sin \frac{\theta_i}{2}$, $C_a = \cos \frac{\alpha_i}{2}$, $S_a = \sin \frac{\alpha_i}{2}$, $A = \frac{\alpha_i}{2}$ and $D = \frac{d_i}{2}$. Then, the DQ that maps frame $\{i\}$ to frame $\{i-1\}$ is given by

$$i^{-1} q_i = q_i^Z \otimes q_i^X = [C_{\theta} C_a, C_{\theta} S_a, S_{\theta} C_a, S_{\theta} S_a] + \epsilon \left[ -D S_{\theta} C_a - A C_{\theta} S_a, -D S_{\theta} S_a + A C_{\theta} C_a, D C_{\theta} S_a + A S_{\theta} C_a, D C_{\theta} C_a - A S_{\theta} S_a, \right] \quad (2)$$

For $n$-degree serial manipulator, transformation DQ is $0 q_n = 0 q_1 \otimes \cdots \otimes n^{-1} q_n$.

3.2 Inverse Kinematics (IK) Modelling

Differential kinematics involves mapping differential change in joint parameters $\dot{\theta}$ to differential change in pose $\dot{q}$ by means of Jacobian matrix $J$ as $\dot{q} = J \dot{\theta}$. For non-square Jacobian, pseudo-inverse is determined by using $J^T \dot{q} = J^T J \dot{\theta}$ to obtain $\dot{\theta} = (J^T J)^{-1} J^T \dot{q}$. One way to deal with $(J^T J)^{-1}$ is to approximate it to
\[
\alpha = \frac{\langle \dot{q}, J J^T \dot{q} \rangle}{\langle J J^T \dot{q}, J J^T \dot{q} \rangle} \quad [10],
\]
where \( \langle \cdot, \cdot \rangle \) is a dot product operator. This is called the Jacobian transpose (\( J^T \)) method. To further reduce the chances of \( J^T J \) losing rank, the damped least squares method (DLS) is used [10]. Here, a damping constant \( \delta \approx 0.001 \) in the diagonal elements modifies the expression to
\[
\dot{\theta} = (J^T J - \delta^2 I)^{-1} J^T \dot{q}.
\]
The \( i \)th column of Jacobian \( J \) is
\[
\frac{\partial}{\partial \theta_i} (0, q_n)\]
where \( n = \) number of joints.

For given pose \( q = q_r + \epsilon q_d \), linear velocity \( v \in \mathbb{R}^3 \) and angular velocity \( w \in \mathbb{R}^3 \), the DQ differential operator is
\[
\dot{q} = \frac{1}{2} \xi \otimes q \quad \text{where} \quad \xi = [0, \omega] + \epsilon [0, v + t \times \omega]
\]
is twist in world frame [11] and \([0, t] = 2q_d \otimes q_r^* \). Then, the DQ differential operator becomes
\[
\dot{q} = \frac{1}{2} ([0, \omega] + \epsilon [0, v + t \times \omega]) \otimes (q_r + \epsilon q_d).
\]

For initial pose \( q_0 \) of a serial manipulator, let corresponding joint parameters be \( \theta_0 \). Now, for some \( J(\theta_k) \) and \( \dot{q}_k \), when \( \dot{\theta}_k \) is obtained from IK model, then \( \theta_k \) is updated to \( \theta_{k+1} = \theta_k + \dot{\theta}_k \), and updated pose from FK model becomes \( X_F(\theta_{k+1}) \).

However, due to various reasons such as linearization, this does not match the next pose \( q_{k+1} = q_k \otimes \dot{q}_k \). The pose error, given by \( (q_k)_{k} = X_F(\theta_{k+1})^* \otimes q_{k+1} \), is fed back to the next differential pose \( \dot{q}_{k+1} \),
4 Application to Kuka LBR IIWA 7 R800 Cobot

The classical DH convention [9] is used to assign coordinate frames to the 7-dof Kuka LBR IIWA 7 R800 cobot (or collaborative robot) and derive the robot architecture as seen in Fig. 2.

A library for dual quaternions is developed in Python 3.6 for implementing the algorithms. The tests are performed on a Windows 8 PC with Intel i5-4570 3.2 GHz processor, 8 GB DDR3 RAM and GeForce 625 graphics card. The DQ outputs of forward kinematics model for a series of joint inputs are tallied with results from

<table>
<thead>
<tr>
<th>Joint</th>
<th>$a_i$ (m)</th>
<th>$\alpha_i$ (deg)</th>
<th>$d_i$ (m)</th>
<th>$\theta_i$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>$-\pi/2$</td>
<td>0.34</td>
<td>$\theta_1$</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>$\pi/2$</td>
<td>0</td>
<td>$\theta_2$</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>$-\pi/2$</td>
<td>0.4</td>
<td>$\theta_3$</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>$\pi/2$</td>
<td>0</td>
<td>$\theta_4$</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>$-\pi/2$</td>
<td>0.4</td>
<td>$\theta_5$</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>$\pi/2$</td>
<td>0.4</td>
<td>$\theta_6$</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$\theta_7$</td>
</tr>
</tbody>
</table>

Fig. 2 Cobot under study (a) with frame assignment (b) and DH parameters [9] (c)

Fig. 3 Closed trajectory showing orientation frames
RoboAnalyzer software. The two IK models are applied to the trajectory shown in Fig. 3. The red, green and blue arrows correspond, respectively, to the $X$, $Y$ and $Z$ axes of the end-effector coordinate frame.

5 Results and Discussion

The DQ FK model results matched perfectly with those obtained from the homogeneous transform matrix (HTM) FK model and RoboAnalyzer software. The DQ FK model required 224 additions and 312 multiplications as opposed to 234 additions and 356 multiplications needed in HTM. It is seen that using DQs over HTMs saved computational time, the savings being up to 50% in some cases.

Applying the $J^T$ and DLS methods on the trajectory shows that $J^T$ gives solutions faster, but also gives more jerky motions. For $J^T$, mean solution time ranges from 16 to 33 ms, whereas for DLS, the same ranges from 27 to 66 ms. It is also observed that the DLS method outperforms the Jacobian transpose method when not near singularity. The graphs of two DQ components in Fig. 4 show that fluctuations in DLS method are less compared to those in $J^T$ method. It is seen that the trajectory loop did not get closed in either method, which means pose error is not eliminated even when feedback is used. This makes a case for exploring more feedback controllers.

6 Conclusion

In this work, dual quaternions (DQs) were used to develop the forward and inverse kinematics models for a serial manipulator. The DQ differential operator and two methods of solving inverse differential kinematics with DQs were discussed. The approach was implemented on the Kuka LBR iiwa 7 R800 cobot, and error during simulation of tracing a loop trajectory was studied. Though DQs seem unintuitive

![Graphs showing deviation in J^T and DLS methods](image)

**Fig. 4** Comparison of deviations in trajectory traced with $J^T$ and DLS IK algorithms taking first and sixth DQ elements as example
to humans, they lend themselves well to working with elaborate trajectories. Future works include velocity and acceleration control, as well as DQ implementation of faster IK algorithms such as FABRIK.

References

Performance Analysis of Corrugated Inclined Basin Solar Distillation System Coupled with Parabolic Trough Collector

Sandeep Joshi, Shubham Tagde, Aboli Pingle, Nikhil Bhave, and Tushar Sathe

Abstract Several designs of solar distillation system have been built over the past century. However, the development of an economical system with high productivity is a major challenge. Various researchers worked to improve the productivity of solar distillation system by improving the rate of evaporation and/or the rate of vapor condensation. In the current work, the evaporation rate is enhanced by basin modification and using a secondary heating medium. An inclined corrugated basin solar still is designed and fabricated and coupled with a parabolic trough collector. Experimental study was carried at Nagpur (21.14° N, 79.0882° E) during the months of April and May, and results indicate 13.58% increase in the thermal efficiency. Further, CFD analysis is carried out by using RNG ($k − \varepsilon$) turbulence model in ANSYS Fluent. The CFD results were found to be in good agreement with the experimental results, thus validating the CFD model to carry out any modifications in the future.

Keywords Inclined basin solar still · CFD analysis · Corrugated basin · Parabolic trough collector

1 Introduction

Water is one of the basic human needs. Water treatment amounts for about 8% of global energy consumption [1]. The use of solar still for water treatment and distillation is one of the most popular renewable energy solutions. However, low productivity of solar stills has been a matter of concern.

Several researches have suggested various methods to enhance the productivity of the solar still with the use of fins, multi-basin, energy storage materials [2], wick [3, 4] reflectors [5–7], and coating the absorber surface with different films [8]. Also,
increasing the absorber area is suggested to help improve the performance of solar still which can be achieved by providing corrugations of V-shaped [9], wave-shaped [10], covered absorber plate with copper chips [8], etc. Some investigators have also used the solar collectors like flat plate collector [11, 12], evacuated tube collector [13], tracked parabolic trough collector [14], etc., as secondary heating source.

The present work focuses on the improvement of rate of evaporation. An inclined corrugated basin solar still coupled with a parabolic trough collector is designed and fabricated. The performance of the system is simulated using CFD technique and validated using experimental analysis. The experiments are performed at Nagpur (21.14° N, 79.08° E) in the month of April and May. The details of simulation and experimental studies are discussed in the subsequent text.

## 2 Working Principle

The schematic diagram of the modified system of inclined corrugated basin solar still coupled with parabolic trough collector is shown in Fig. 1. In the modified system, the corrugated basin receives heat from two sources, viz. incident solar radiations and the parabolic trough collector.

The parabolic trough collector acts as the secondary heating source which heats water, and the heat of the water is then passed through the corrugated channel in the basin. This water is recirculated in the heating water circuit of parabolic trough collector. The raw water to be distilled is circulated over the basin via header pipe. The header pipe is drilled at specific interval in such a way that the raw water falls drop by drop over the basin and thus get heated and evaporates. The evaporated water is condensed as it encounters the top glass, and thus, the distilled condensate is collected. The corrugated basin is modified by providing well-designed V-shaped corrugations and orienting it in inclined position to increase the surface area of the absorber plate.

![Fig. 1 Schematic diagram of the inclined corrugated basin solar still coupled with parabolic trough collector](image-url)
3 Experimental Analysis

The experimentation setup consists of conventional horizontal basin, corrugated basin, evacuated tube collector, and parabolic trough collector as shown in Fig. 2. Adequate piping arrangement has been done to circulate the heated water from the parabolic trough collector to the basin of solar still.

During experiments, the basin temperature of both the solar stills, glass temperature, temperature of inlet water and outlet water from the parabolic trough collector were recorded throughout the period. The productivity of both the solar still was recorded by measuring the distillate output time to time.

4 Computational Analysis

Geometry of corrugated inclined basin solar still was created in CATIA simulation software. The geometry file was then imported in ANSYS Fluent. The rectangular meshing was generated by AUTOMESH. Average value of the solar irradiance at the given location and average estimated temperature values were given as input. Glass front, and back wall temperatures were constant. Heat flux, opaque thermal, and semitransparent conditions were implemented on; front, side, and back walls of corrugated absorber plate and glass, respectively.

The \(k - \varepsilon\) turbulence model is the most common model used in CFD to simulate mean flow characteristics for turbulent flow conditions. However, RNG \( (k - \varepsilon)\) model is selected for analysis as it gives a general description of turbulence by two transport equations. The turbulent kinetic energy Eq. (1) is same as in case of \(k - \varepsilon\) turbulence model; however, there is an additional term in its \(\varepsilon\) Eq. (3) which is significant in improving the accuracy for rapidly strained flows.
Equation of turbulent kinetic energy ($k$)

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k x)}{\partial x} = \frac{\partial}{\partial x} \left[ \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x} \right] + 2\mu_t E_{ij} E_{ij} - \rho \varepsilon$$  \hspace{1cm} (1)

Equation of rate of dissipation of turbulent kinetic energy ($\varepsilon$) in ($k - \varepsilon$) model

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x} = \frac{\partial}{\partial x} \left[ \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x} \right] - C_1 \varepsilon \frac{\varepsilon}{k} - 2 C_1 \varepsilon \frac{\varepsilon}{k} 2 \mu_t E_{ij} E_{ij} - C_2 \rho \frac{\varepsilon^2}{k}$$  \hspace{1cm} (2)

Equation of rate of dissipation of turbulent kinetic energy ($\varepsilon$) in RNG ($k - \varepsilon$) model

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x} = \frac{\partial}{\partial x} \left[ \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x} \right] - C_1 \varepsilon \frac{\varepsilon}{k} - 2 C_1 \varepsilon \frac{\varepsilon}{k} 2 \mu_t E_{ij} E_{ij} - C_2 \varepsilon \rho \frac{\varepsilon^2}{k} - R_e$$  \hspace{1cm} (3)

4.1 CFD Analysis

The temperature contours of the inclined corrugated solar still and glass cover are shown in Fig. 3a, b, respectively. It is observed that the mean temperature of the inclined corrugated basin is 335 K.

Fig. 3  a Temperature contour for corrugated inclined basin solar still, b temperature contour for glass cover
It is observed that the mean temperature of the glass cover is around 302 K. Based on the CFD analysis, the productivity of the modified solar still is calculated to be equal to 279 ml/h.

5 Result and Discussion

5.1 Experimentation Results

Figure 4 shows the variation of average distillate output of conventional and corrugated solar still along with variation in solar radiation intensity with respect to the time of the day.

It observed that corrugated inclined solar cell provided higher productivity than the conventional system irrespective of the time of the day. It can be observed that the highest output for conventional and corrugated solar still was found to be 204 ml/h and 232 ml/h, respectively, at 1300 h.

The variation of average instantaneous experimental and theoretical efficiencies of conventional and corrugated basin solar still with respect to time is shown in Fig. 5. The efficiency of corrugated solar still was found to be higher, i.e., 32.9% as compared to that of conventional solar still which was just 23.62%.
6 Conclusion

The present work focuses on the productivity improvement of the solar still by improving its rate of evaporation. An inclined corrugated basin solar still is designed. The inclined basin is modified as a corrugated channel, and it is coupled with a parabolic trough collector. The heat from the parabolic trough collector is transferred to the modified basin using suitable flow arrangement. Thus, the basin surface receives heat from direct solar radiations as well as from the coupled parabolic trough collector.

The performance of the system is simulated using CFD technique. The simulation results show the improved performance of the modified system over conventional one. The CFD results are validated by the experimental analysis. The modified solar distillation system is fabricated. The experiments are performed at Nagpur (21.14° N, 79.08° E) in the month of April and May. The current work, solar still basin modification, and secondary heating source are used to enhance the overall productivity of solar still. Based on the experimental study, it was observed that the productivity of the conventional solar still was found to be 204 ml/h and that by modified solar still was 232 ml/h thus giving a clear indication of productivity improvement. Also, the efficiency of corrugated solar still was found to be higher, i.e., 32.9% as compared to that of conventional solar still which was just 23.62%. The CFD simulation shows good agreement with the experimental results, thus validating the CFD model to carry out further modification in the system.