Modeling and Assessing of Self-Reconfigurable Cleaning Robot hTetro Based on Energy Consumption

Abdullah Aamir Hayat *, Parasuraman Karthikeyan, Manuel Vega-Heredia and Mohan Rajesh Elara

Engineering Product Development Pillar, Singapore University of Technology and Design (SUTD), Singapore 487372, Singapore; pvkarthi45654@gmail.com (P.K.); manuel_vega@sutd.edu.sg (M.V.-H.); rajeshelara@sutd.edu.sg (M.R.E.)

* Correspondence: abdullahhaamir@sutd.edu.sg

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Abstract: The autonomous floor-cleaning self-reconfigurable robots have entered into the practical stage by establishing enhanced area coverage over the fixed morphology counterparts. Energy consumption during the self-reconfiguration, i.e., changing the shape of the robot from one form to another, becomes a primary focus in these robots that carry finite energy sources. In this paper, hTetro platform with two hinge dissections namely, Left–Left–Left (LLL) and Left–Left–Right (LLR) are modeled and assessed for the energy consumption during the reconfiguration. The geometry of the two dissections, its workspaces, and the set of inverse kinematics solutions for the seven forms are presented. The inverse dynamics using the Newton–Euler approach was adopted to calculate the wrench, i.e., forces and moments at the hinge joints, and subsequently assess the power consumed during the reconfigurations of two hinge dissections in the simulation. Extensive experiments were performed across the two assembled platforms to estimate the power consumption by logging the current data. The comparison was made with the simulation results. The results are particularly useful in the selection of reconfiguration with minimal energy consumption during the floor cleaning.

Keywords: hTetro; reconfigurable robot; workspace; dynamic modeling; power consumption

1. Introduction

Floor cleaning in a commercial and domestic environment is usually a monotonous, tedious, and boring task, and thus robots are a viable alternative option to perform such tasks. The floor cleaning problem has attracted many researchers as it extends the focus on the problem of path planning, the design of the robot, executing autonomous motion, and area coverage in an unstructured environment. Many commercially available cleaning robots, like iRoomba, Samsung Powerbot, Bobsweep, Moneual RYDIS, Miele scout, Infinuvo Clean Mate, etc., are available with autonomy and path planning features. However, these fixed morphology robots are generally either equipped with selected modules like wet mopping, dry cleaning, autodocking for recharge and vacuum modules. Apart from this, one major factor for their performance loss is due to fixed morphology design. Their fixed physical morphology act as a constraint on the area covered in the unstructured environment where the shape, size, and location of obstacles like narrow spaces between furniture, room corners, and curved passages are unknown during navigation.

The design philosophy of mechanically transformable shape or self-reconfigurability is beneficial to implement in a cleaning robot to overcome the above-discussed pitfalls. Reconfigurable systems are defined as those that can reversibly attain distinct configurations or states via alternating system form or function to achieve the desired outcome within acceptable reconfiguration time, cost, and energy [1]. The mechanism reconfigurability is classified as intra-reconfigurability and
inter-reconfigurability [2]. An intra-reconfigurable robot can be viewed as a collection of components (sensors, actuators, mechanical parts, power sources, controllers, etc.) acting as a single entity while having the ability to change, for instance, its structure, mobility, or principal activity without requiring any external assembly or disassembly. The inter-reconfigurability defines to what extent a robotic system can change its morphology through assembling and disassembling its robotic components. In [2], the self-reconfigurable mobile robot, called Hinged-Tetro, was conceived for the first time. It was based on the theory of hinged dissection of polyominoes as reported in [3] and was inspired from the tile-matching puzzle video game called “Tetris”, which consists of four identical square blocks that can transform into seven shapes, therefore named as hinged-Tetro.

In the first reported work on hinged-Tetro [2], the hinged dissection of polyominoes was described in detail. Using theorems on hinged dissection in which using the lemmas it was proved that the hinged Tetromino (hTetro) can be dissected as \{LLL, LLR, LRR, RLL, RLR, RRL, and RRR\} [4,5]. It was proved that only LLL and LLR dissection could attain all the required one-sided transformations or forms named as \{I, J, L, O, S, T, Z\} on the basis of shape as shown in Figure 1. The one-sided polyominoes are distinct when none is a translation or rotation of another (geometry cannot be flipped over). Note that the two pairs, i.e., \{L, J\} and \{S, Z\}, of tetrominoes look very similar, but we cannot rotate one of them to get the other. In an extension of this work the nested reconfigurability and reported initial tests with hTetro-LLR without the dynamic modeling of the system [6].

In this paper, we carried out the detailed and systematic measure for the power consumption during the reconfiguration of both the architectures, i.e., hTetro-LLL and hTetro-LLR with its dynamic modeling, simulation, and experimental results. Moreover, with this study, one can understand the current consumption and behavior of hTetro reflected by the movement of each hinge motor during reconfiguration. As hTetro is designed to perform the floor cleaning task, the efficient area coverage of hTetro over the fixed morphology robots was compared [7,8]. Experimentally, they observed that hTetro covered 95% of the area in a given fixed environment.

Functional modeling is a key step in the product design process, whether using the original or redesigns with the inductive approach [9]. Figure 2 depicts the advantages of the reconfigurable floor cleaning robot in terms of covering sharp edges, area coverage in an unknown environment. In this work, we have built the hTetro-LLL and hTetro-LLR, as shown in Figure 2b,c, respectively, with each of its block designed for higher payload using four omni-wheels. The four omni-wheels in each module will provide mechanical stability to the base along with the higher acceleration over the three omni-wheels [10]. The pavement sweeping robot with reconfigurability and differential wheels were presented in [11]. The matrices for analyzing the performance are, measurement of the covered area using computer vision technique and the distance covered by the cleaning robot [12] which depends on the energy consumption. To evaluate the optimal configuration of the self-reconfigurable robot which will help to improve power management will be extremely useful for energy-efficient performance.
Simulation of robotic systems is useful to predict its behavior which starts with the modeling of the system. Dynamic modeling is concerned with the derivation of equations of motion (EOM) of a system at hand. Several methods for formulating EOM like, Newton–Euler (NE), d’Alembert’s principle, Euler–Lagrange principle, Gibbs–Appell approach, and Kane’s method [13]. In [14], the simulation model was made in Simulink and the reconfiguration, for only two shapes gained by hTetro, was taken into account, i.e., I to J with a single architecture, i.e., hTetro-LLR only. The assembled platform has reconfiguration and locomotion occurring separately, i.e., platform is stationary about the second block #2 (which has the locomotion unit with powered wheels, power sources, and navigation sensors) while the reconfiguration takes place. In the present work, we put emphasis on calculating the energy while reconfiguration occurs in all the shapes, and we considered two variants of the hTetro architecture. We used the Newton–Euler approach to model the hTetro reconfiguration as it is obtained from the free body diagram and is suitable to analyse internal forces and torques at the joint. The NE formulation involves computation of link by link velocities and acceleration starting from the base to last link. Using this relationship of kinematics and the dynamic equations, wrench, i.e., the moment and forces are computed. The joint reaction forces at the hinge joints along with the torque required by the hinge joints during the reconfiguration of the hTetro are analyzed in this work. A systematic approach for calculating the power in simulation is derived first by formulating the dynamics using the Newton–Euler approach for calculating torque and then from this torque and trajectory information power is calculated. We have explained the steps to estimate the energy both in simulation and experiments.

Figure 2. Floor cleaning robotic platform hTetro (a) accessing narrow passages (b) hTetro-LLL across circular section, and (c) hTetro-LLR across circular section.

Energy-efficient operation is vital, as it reduces energy losses and transmission costs, boosts the duty time of the energy storage units, and gives an opportunity to reduce the capacity and price of such units. The approaches for electricity consumption characteristics and energy-saving possibilities for an industrial robot [15]. In terms of speed and energy consumption, it was reported that spherical configuration is superior to the joint arm, cylindrical, or rectangular design of industrial robot [16]. Energy savings becomes vital in wheeled mobile robot as it is supplied from the finite on-board source as batteries. The other aspects of energy saving in mobile robots with fixed morphology were presented [17,18]. It was reported that the energy consumed by the motor strongly depends on the trajectory profile to reach the desired speed on the given final time [19]. In this study, we analyze the power consumption in simulation and experiments by giving the joint trajectory profile for the
reconfiguration in fixed time. To the best of the authors’ knowledge, this is the first time the energy consumption during the reconfiguration in a self-reconfigurable class of robots is assessed by modeling in a simulation and then performing the experiments.

Taking cognizance from the above introduction, we set the following objectives.

- Kinematic comparison of the two dissections, i.e., hTetro LLL and LLR, along with the tabulated results for the inverse kinematics solutions for different forms.
- Study the hinge joint’s torque and reaction forces, also called shaking forces, and moments at the hinged joints during the reconfiguration in the simulation. Apply the inverse dynamics for the given geometric, mass, and inertia properties of hTetro obtained from CAD, and subsequently calculate power consumption during the reconfiguration in the simulation.
- To perform extensive experiments using the assembled hTetro in its LLL and LLR architecture for estimating the power using the logged current data from each hinge joint during the reconfiguration.

This paper is divided into six sections. Section 2 gives the details about the design and functionality of the self-reconfigurable hTetro robot. The kinematic formulation and the workspace analysis for the two architecture, i.e., hTetro-LLL and LLR were presented in Section 3. Section 4 presents the simulation and modeling to calculate the power consumption during reconfiguration followed by the extensive experimental results and discussion in Section 5. Finally, Section 6 concludes the paper.

2. hTetro Design

The hTetro is designed to reconfigure its shape in one of the forms, i.e., {L, J, L, O, S, T, Z}, to have a greater area coverage by accessing the narrow spaces by changing its shape and is also helpful in avoiding the collisions. This also opens a new field for tiling-based theories for the area coverage [20]. The hinged Tetromino (hTetro) has four identical blocks which are of cuboid shape. The cuboid shape of each block allows an easy intra-reconfiguration process while providing enough space to allocate appropriate sensors and modules. The internal ribbing in each block provides the necessary strength. The dimensions of the four blocks are as follows, namely, #1, #2, #3, and #4, having length and breadth equal to 250 mm and heights of 140 mm. Acrylic sheets having 4 mm thickness were used to cover the top and sides of the robot. In this work, we considered two sites for the hinge joint connecting the blocks #3 and #4, and on this basis, it is labeled as hTetro-LLL and hTetro-LLR. Figure 3 shows the system architecture of the hTetro-LLL with the hinge joint site for LLR. Each block is responsible for a particular function as shown in Figure 3. These two geometries have a high potential for research in nested reconfiguration since it has the advantages of inter- and intra-reconfigurability that results in more complex morphologies. In this paper, we focus on assessing the intra-reconfigurability features of the two architectures of hTetro, which will assist in utilizing the architecture efficiently for the area coverage problem [7].

The design of the two architectures was done keeping in mind the modularity and mass production. Blocks #1, #2, and #4 were kept the same in both the architecture, i.e., LLL and LLR. Only in #3 the location of hinge joint was changed from left (L) to right (R) corner of the cuboid, keeping the internal components intact. Block #2 works as a frame that docks the motors for the rotations of Blocks #1 and #3. Block #2 is acting as the anchor of the system that is not supposed to move during the reconfiguration. The mass of this block was kept highest among the three to decrease the effect of shaking forces and moments that arises due to the rotation of other blocks [21,22]. Accordingly, all the bulky robot subsystems, such as electronics, power source, drive systems, etc., are placed in #2. The four motors powering the omni-wheel for the locomotion of the system was also assembled in #2.
The reconfigurability of hTetro is guaranteed by three revolute joints that connect the constituent blocks in a chain formation. The single-axis rotation provided by each hinge joint allows its adjacent blocks to rotate with a range of motion of up to 180°. To facilitate the mobility of each block during the reconfiguration, four omni-wheels were attached in each block. In the present work, these wheels were kept passive and provides the free movement in the Euclidean plane during the rotation of blocks while reconfiguring. Also, the four-point contact of each block gives stability during mobility. To achieve faster and stable locomotion with higher payload carrying capacity, all the four omni-wheels in each block can be powered and poses an interesting control problem of locomotion while reconfiguration without the hinge motors will be dealt in future.

Note the assumptions that are taken while performing kinematics and dynamics of the hTetro in the next sections:

1. The geometric shape of each link of the hTetro are same, and throughout the reconfiguration link 2 or #2 is stationary. As a result, during reconfiguration, it acts as a system of two serial chains one with a single link (#1), and another with two links (#3 and #4) connected to #2.
2. The mass and inertial properties of each link are different. This is based on the fact that each link carries a different payload as per the design. Link 2 is heaviest since it carries the necessary power source, electronics, controllers and the dead loads as well.
3. The four omni-wheels attached at equidistant from the geometric center of each link that shares the load equally. They are assumed to be passive throughout this work since the reconfiguration is only due to the action of hinge motors.

3. Kinematics

Kinematically, we treat the self-reconfigurable robot hTetro as two serial chains: One branch with a single link (#1) attached to Block #2, and the second branch of the chain with two links (#3 and #4) attached with #2. It is depicted with two subsystems in Figure 4b. The major difference in the two architecture is the link length and the joint rotation direction of the third link. The frame assigned in two dissections is shown in Figure 4a,c, respectively. Note that the two subsystems are considered for the ease of kinematic and dynamic formulations with block-2 assumed to be the center block about which the two subsystems are labeled as in Figure 4b. Table 1 lists the Denavit–Hartenberg (DH) parameters notation as adapted in [23] for the two dissections of the hTetro.
Here, we use a graphical approach to calculate the workspaces of the two dissections of hTetro, i.e., -LLL and -LLR. The assumption was made that block-2 is not moving or actuated while the reconfiguration takes place. This gives an idea of the possible area coverage from a given fixed configuration (here, I-configuration) as shown in Figure 5a. The steps for calculating the workspace are as follows. (a) Plot the initial configuration of the platform on the scale and convert it to binary image. (b) Estimate the correspondence between the pixel count and the black pixel count as per the joint limits and calculate the workspace or covered area by counting the pixels. Here, for hTetro-LLL, the joint angle variations as $0 < \phi_1 < \pi$, $0 < \phi_2 < (-\pi)$ and $0 < \phi_3 < (-\pi)$, and for hTetro-LLR $0 < \phi_1 < \pi$, $0 < \phi_2 < (-\pi)$ and $0 < \phi_3 < (\pi)$. The black pixel count corresponding to the hTetro-LLL was 294,235 pixels and for hTetro-LLR was 377,280 pixels, both are shown in Figure 5b,c, respectively. It is concluded that hTetro-LLR has approximately 22% greater
workspace than the hTetro-LLL. This method is generic and can be used to calculate the workspace of any planar mechanisms with arbitrary shapes.

![Diagram](image)

(a) Initial configuration of hTetro in I-shape and its covered area black pixels  
(b) Workspace of hTetro-LLL and its covered area in black pixels  
(c) Workspace of hTetro-LLR and its covered area in black pixels

**Figure 5.** The workspace comparison of the two dissections.

The inverse kinematic solutions, i.e., the hinge joint angular position values corresponding to the given form or shape of the hTetro, i.e., [I, J, L, O, S, T, and Z] for the two dissections, are listed in Table 2 with I assumed to be in zero position, where \( \phi_1 = \phi_2 = \phi_3 = 0 \). Note that the matrix of the inverse kinematic solution is having the elements \((IK)_{ij} = -(IK)_{ji}\), where \(i\) and \(j\) contains the set of 7 forms and the diagonal elements do not contain any transformation values. Table 2 is useful while commanding the intra-reconfiguration operation for this finite state machine having seven states, i.e., one for each of the one-sided tetrominos. Next, the expression for angular and linear velocities of each link are derived.

**Table 2.** Kinematic transformation table for the seven forms, i.e., [I, J, L, O, S, T, Z] from one to another for hTetro-LLL and hTetro-LLR. Note that \(\ast\), i.e., the elements in lower triangular part of the table are negative of the upper triangular elements. For example in hTetro-LLL, \([I \rightarrow J]\) has \(\phi_2(-\pi)\) then \([J \rightarrow I]\) is \(\phi_2(\pi)\).

|   | I   | J   | L   | O   | S   | T   | Z   |
|---|-----|-----|-----|-----|-----|-----|-----|
| I | LLL | LLL | LRR | LLL | LLL | LLL | LLL |
| J | LLL | LLL | LRR | LLL | LLL | LLL | LLL |
| L | LLL | LLL | LRR | LLL | LLL | LLL | LLL |
| O | LLL | LLL | LRR | LLL | LLL | LLL | LLL |
| S | LLL | LLL | LRR | LLL | LLL | LLL | LLL |
| T | LLL | LLL | LRR | LLL | LLL | LLL | LLL |
| Z | LLL | LLL | LRR | LLL | LLL | LLL | LLL |

**Note:** The elements in lower triangular part of the table are negative of the upper triangular elements. For example in hTetro-LLL, \([I \rightarrow J]\) has \(\phi_2(-\pi)\) then \([J \rightarrow I]\) is \(\phi_2(\pi)\).
3.1. Link Kinematics

Figure 4a shows the world frame $\{W\}$ with its axes $X_w, Y_w$. Each link is assigned with the local frame attached at the origin of each hinge joint as $O_i$. Each link has local Cartesian frame, $X_i, Y_i, Z_i$, where $Z_i$ is along the cross product of $X_i$ and $Y_i$. The two subsystems, i.e., one with one link and other with two links will have the linear and angular velocities expressed as:

$$\omega_1 = \dot{\varphi}_1 e_1, \quad \dot{c}_1 = v_H + \omega_1 \times d_1$$

$$\omega_2 = \dot{\varphi}_2 e_2, \quad \dot{c}_3 = v_H + \omega_2 \times d_3$$

$$\omega_3 = \omega_2 + \dot{\varphi}_3 e_3, \quad \dot{c}_4 = v_H + \omega_2 \times a_3 + \omega_3 \times d_4$$

where $e_i$ for $i = 1, 2, 3$ are the direction vectors of joint rotations. The second link length, $a_2$, is the distance from link origin $O_2$ to $O_3$. In this paper, we assume that the link 2 is not moving and can be assumed as clamped; therefore, the translational velocity due to locomotion of the hTetro $v_H = 0$. Considering $\omega_i$ and $v_i \equiv \dot{c}_i$ as the angular velocity and the linear velocity of the origin point, $O_i$, of the $i$th link twist vector is defined as, $t \equiv [\omega^T v_H]^T$. Next, due to the hinge rotation, as shown in Figure 4, the rotation of the passive wheels are discussed.

3.2. Kinematics of Wheel Due to Hinge Movement

The mass of each rigid body links or modules are listed in Table 3. The moment of inertia of each link depends upon two factors: (1) the distribution of mass and (2) the location and direction of the axis of rotation. Figure 4a shows the geometric center and center of mass of say $i$th-link of hTetro. If each module is independent to move with the actuation of four omni-wheels, then the rotation will occur about the axis passing through its center of mass [24]. It is inferred that during reconfiguration of hTetro without any locomotion, the hinge joints constraints the motion of each omni-wheels. Assuming the omni-wheels in #1, #3 and #4 as passive, the movement of hinge joint will induce the rotational motion to the omni-wheels. The velocity vector of each wheel at its point of contact with the ground due to the rotation of the hinge joint is given by:

$$v_{ij} = v_H + \omega_i \times r_{ij}$$

where, the velocity of the hTetro or complete vehicle $v_H = 0$. Each wheel center position vector is given by $r_{ij}$ from the hinge joint origin of link $i$ to the center of the wheel $j$, as shown Figure 4d. Two unit vectors, $e_{ij}$ and $s_{ij}$, are assigned at the point of contact of the wheel with the ground as shown in Figure 4d. The unit vector $e_{ij}$ is the axle direction, and $s_{ij}$ is orthogonal to $e_{ij}$ and gives the instantaneous direction of each wheel rotation. The component of velocity given by Equation (4) will result in the rotation of wheel with radius $\rho^w$ and the passive rotation of the barrel with radius $\rho^b$. The condition for rolling without slipping is given by:

$$v_{ij} \cdot s_{ij} = \theta_{ij} e_{ij} \times \rho^w n_{ij}$$

$$v_{ij} \cdot e_{ij} = \theta^b s_{ij} \times \rho^b n_{ij}$$

where $\theta_{ij}$ is the angular speed of the $j^{th}$ wheel attached to $i$th link and $\theta^b$ is the barrel angular rotation speed. Unit vector $n_{ij}$ is along the radius of wheel and normal to unit vectors $e_{ij}$ and $s_{ij}$. The above expression will guide the actuation of each wheel rotation, to prevent slipping while reconfiguration without locomotion. The reconfiguration with locomotion is not the objective of present work and will be dealt later.
4. Modeling and Simulation

The dynamic analysis of a self-reconfigurable robot is carried out to evaluate the moments and the joint reaction forces for the two dissections selected in this paper. We presented the inverse dynamics formulation to calculate the generalized force, i.e., torque and forces coming at the hinge joints. The inertia properties, namely, mass, the position of the center of mass, and inertia tensor, were calculated from the CAD model by assigning the material property to the link. These are listed in Table 3.

Table 3. The parameters \( r_x, r_y, r_z \) are component of vector \( r \), i.e., length from center \( O \) to center of mass (COM) \( C \) as in Figure 6, with dynamic parameters of \( m \) for mass (kg) and \( I \) for inertia (kgm^2) about the link COM.

| Blocks | 1    | 2    | 3    | 4    |
|--------|------|------|------|------|
| \( m \) | 1.70 | 3.80 | 1.90 | 1.75 |
| \( r_x \) | 0.125 | 0.125 | 0.125 | 0.125 |
| \( r_y \) | 0.125 | 0.125 | 0.125 | 0.125 |
| \( r_z \) | 0.075 | 0.082 | 0.075 | 0.075 |
| \( I_{zz} \) | 0.0181 | 0.0522 | 0.0202 | 0.0181 |

Figure 6. Free body diagram for ith-link in serial chain system.

4.1. Newton–Euler Equations of Motion

Euler’s and Newton’s equations of motion of the ith rigid link in a serial chain of Figure 6a are written from its free body diagram, shown in Figure 6b, as

\[
\mathbf{I}_i \dot{\mathbf{\omega}}_i + \mathbf{\omega}_i \times \mathbf{I}_i \mathbf{\omega}_i = \mathbf{n}_i^f
\]

\[
m_i \ddot{\mathbf{c}}_i = \mathbf{f}_i^e
\]

where \( \mathbf{n}_i^f \) is the resultant external moments and \( \mathbf{f}_i^e \) is the resultant force acting about the link’s center of mass (COM), \( C_i \). Moreover, \( \mathbf{I}_i \) is the inertia tensor with respect to \( C_i \). The angular velocity of the link is defined by \( \mathbf{\omega}_i \equiv [\omega_x, \omega_y, \omega_z]^T \) and its linear acceleration is \( \ddot{\mathbf{c}}_i \equiv [\ddot{c}_x, \ddot{c}_y, \ddot{c}_z]^T \). Furthermore, the \( 3 \times 3 \) cross-product matrix associated with the angular velocity \( \mathbf{\omega}_i \), i.e., \( \mathbf{\omega}_i \), is introduced as

\[
\mathbf{\omega}_i \equiv \mathbf{\omega}_i \times 1 \equiv \begin{bmatrix}
0 & -\omega_z & \omega_y \\
\omega_z & 0 & -\omega_x \\
-\omega_y & \omega_x & 0
\end{bmatrix}
\]

Note that the permissible motion between the two constitutive links is due to the joint whose axis is passing through link origin \( O_i \) as shown in Figure 6b along the unit vector \( \mathbf{e}_i \). To express the NE
equations of the $i$th link with respect to the origin of the link, $O_i$, the velocity, $\dot{c}_i$, and the acceleration, $\ddot{c}_i$, are to be expressed by taking the derivatives of position vector $c_i = o_i + d_i$ as

$$\dot{c}_i = \dot{o}_i + \omega_i \times d_i$$

$$\ddot{c}_i = \ddot{o}_i + \omega_i \times (\omega_i \times d_i)$$

(10)

Also, the inertia tensor about $O_i$, namely, $I_i$, resultant force, $f_i$, and the resultant moment $n_i$ about $O_i$ are as follows,

$$I_i' = I_i + m_i \ddot{d}_i$$

$$f_i' = f_i$$

$$n_i' = n_i - \ddot{d}_i f_i$$

(11)

where $\ddot{d}_i$ is the $3 \times 3$ skew-symmetric cross product matrix associated with the vector $d_i$. Substituting Equations (10) and (11) into Equations (7) and (8), the NE equations of motion for the $i$th link can be represented with respect to the origin $O_i$ as

$$n_i = I_i \omega_i + m_i d_i \times \ddot{o}_i + \omega_i \times I_i \omega_i$$

$$f_i = m_i \ddot{o}_i - m_i d_i \times \ddot{\omega}_i - \omega_i \times (m_i d_i \times \omega_i)$$

(12)  

(13)

The above equations of motion can then be written in compact form in terms of the 6-dimensional (6D) twist $t_i \equiv [\omega_i^T \ \upsilon_i^T]^T$, twist-rate $\dot{t}_i = [\dot{\omega}_i^T \ \dot{\upsilon}_i^T]^T$, and wrench $w = [n_i^T \ f_i^T]^T$ as

$$M_i t_i + W_i M_i E_i t_i = w_i$$

(14)

where $M_i$, $W_i$, and $E_i$ are the $6 \times 6$ matrices of mass, angular velocities, and elementary matrix, respectively, as

$$M_i = \begin{bmatrix} I_i & m_i \ddot{d}_i \\ -m_i \ddot{d}_i & m_i I_i \end{bmatrix} \quad W_i = \begin{bmatrix} \ddot{\omega}_i & 0 \\ 0 & \ddot{\omega}_i \end{bmatrix} \quad E_i = \begin{bmatrix} 1 & O \\ O & O \end{bmatrix}$$

(15)

The notations $1$, $O$, and $0$ in Equation (15) represent identity matrix, null matrix, and null vector whose sizes are compatible to the expressions where they appear. In Equation (14), $w_i \equiv w_i^D + w_i^E + w_i^C$, in which $w_i^D$ is the wrench due to driving or actuating moments and forces, and $w_i^E$ and $w_i^C$ are the external and constraint wrenches, respectively. The external wrench, $w_i^E$, is due to the moments and forces of gravity, friction, joint actuators, environmental effects, etc. The constraint wrench, $w_i^C$, is due to the presence of reaction moments and forces at the joint interfaces.

We estimated the torque and reaction forces at each hinge joint during the reconfiguration. The inertial parameters were taken from the CAD model and are listed in Table 3. We have used the quintic trajectory using the 3–4–5 interpolating polynomial [25] for the revolute hinge joints as

$$\phi(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 = \sum_{i=0}^{5} a_i t^i$$

(16)

Differentiating the above equation w.r.t. time, we get the angular velocity and acceleration as

$$\dot{\phi}(t) = \sum_{i=0}^{5} ia_i t^{i-1}, \text{ and, } \ddot{\phi}(t) = \sum_{i=0}^{5} (i-1)a_i t^{i-2}$$

(17)

where $a_i(i=1, \ldots, 5)$ are the coefficients that were derived from the initial and final state of the joints. The velocity and acceleration for linear actuation and rotation, i.e., $l, \theta$ and $\dot{l}, \dot{\theta}$, were found by taking the first and second order derivatives of Equation (16). The detailed trajectory equations with its derivatives [25]. This trajectory was used to actuate the joints from its initial to final position in time
$T = 2.5 \text{ s}$. The hinge joint actuated from $0^\circ$ to $90^\circ$ and $180^\circ$ to $0^\circ$ are shown in Figure 7a,b, respectively. In this paper, we put a time constraint for reconfiguration from one form to another as $t = 2.5 \text{ s}$.

Figure 7. Quintic trajectory for inverse dynamics during reconfiguration using hinge joints.

With the known dynamic properties, i.e., mass, mass moments, and inertia, and the known quintic trajectory for the joint motion in a given time, the joint reaction forces and the torque at each joint are shown in Figure 8. The power due to constraint wrenches is equal to zero, and the power during reconfiguration is only due to the torque required to actuate each hinge joints during the reconfiguration. We have used the results obtained from the inverse dynamics in simulation to calculate the power required during the reconfiguration as discussed in next. The discussion on simulation results are done afterwards.

Figure 8. Joint reaction forces components and the joint torque at each of the three hinge joints during reconfiguration. Detailed results with video in simulation are presented in [26].
4.2. Power Consumption Calculation in Simulation

The total power consumption in a rotational system with the information on torque required and joint trajectory is calculated in two steps. First, the power consumed by each joint, and then the summation of each joint power to get the total power.

\[ P_i(k) = \sum_{k=t_0}^{t_f} \frac{\tau_i(k)\phi_i(k)}{\eta_{mech,i}\eta_{elec,i}} \]

where \( n \) is the degrees of freedom (DOF), \( \tau_i \) is the torque at the \( i \)th joint, \( \phi_i \) is the angular velocity of the \( i \)th DOF, \( t_0 \) is the initial time, \( t_f \) is the end time (here for reconfiguration), and \( \eta_{mech,i} \) and \( \eta_{elec,i} \) are the mechanical and electric efficiencies of the \( i \)th drive, respectively. Equation (18) is basically the definition of power, i.e., equivalent to the product of the torque and angular velocity and has the unit as watts and Equation (19) is the summation for all joints. We used trapezoidal numerical integration to calculate the area under the torque and angular velocity plot, which is equivalent to the power. We used inbuilt command in MATLAB, i.e., \( Q = \text{trapz}(X,Y) \), which integrates \( Y \) with respect to the coordinates or scalar spacing specified by \( X \). Here, \( X \) and \( Y \) are angular velocity of hinge joints (for quintic profile refer Figure 7) and the computed torque \( \tau \) using inverse dynamics.

A detailed discussion on the simulation results, which reflects on the variation of reaction forces at the hinge joint 1, i.e., \( F_{12,X}, F_{12,Y} \), due to the rotation of #1 on #2 at joint 1; \( F_{32,X}, F_{32,Y} \), due to the rotation of #3 on #2 at joint 2; and \( F_{43,X}, F_{43,Y} \), due to the rotation of #4 on #3 at joint 3 along with the three hinge joint torques, i.e., \( \tau_1, \tau_2, \) and \( \tau_3 \) (as shown in Figure 8), is given next.

4.3. Discussion on Simulation Results

The Newton–Euler formulation discussed in this section was used to calculate the required torque and the reaction forces at the hinge joints. Equation (16) is used to actuate the joint, and the power consumption during the reconfiguration was calculated using Equation (18), in which the angular velocity was taken from the trajectory input and the torque was estimated using the inverse dynamics. The mechanical and electric efficiencies discussed in detail in [27] were assumed as 0.50 and 0.70, respectively, in the present work. The mechanical efficiency was taken considering the factors like, friction losses at joints and also due to the friction at the contact of omni-wheels that rotates during the reconfiguration.

The joint reaction forces or shaking forces components denoted by \( F_{12,X}, F_{12,Y}, F_{32,X}, F_{32,Y} \), and \( F_{43,X}, F_{43,Y} \) along with the three hinge torques as \( \tau_1, \tau_2, \) and \( \tau_3 \) at the hinge joints during reconfiguration are shown in Figure 8. Note that \( F_{12,X} \) is read as X-component of the force on block #2 due to rotation of #1, \( F_{12,Y} \) as X-component of the force on block #2 due to rotation of #1, and so on. We have shown only three states of reconfiguration for brevity. Meanwhile, the analysis was carried for all the 42 states transition and in simulation the transition from \( \{i \to j\} = \{j \to i\} \) where \( i \) and \( j \) are one of the seven states. Reconfiguration involving the hinge rotation of all three joints from \( \{I \to T\} \) are shown in Figure 8a,d, for hTetro-LLL and hTetro-LLR. Reconfiguration involving hinge rotation of two joints from \( \{I \to J\} \) are shown in Figure 8b,e and involving single rotation from \( \{I \to L\} \) are shown in Figure 8c,f for hTetro-LLL and -LLR, respectively. Note that we have assumed that #2 was kept stationary during reconfiguration. The shaking forces and moments from \( \{I \to L\} \) for both the architecture were exactly the same and is evident as well because of the same magnitude of rotation of identical blocks. It was observed that the hTetro-LLR has higher shaking forces at its hinge joints due to the location of the hinge joints and the rotation directions during the reconfiguration. The torque and reaction forces in the hTetro-LLR were observed to be higher than hTetro-LLL.
The power consumption during the reconfiguration of the two platforms was listed in matrix form in Figure 9a,b for HTetro-LLL and LLR, respectively. The table lists down the power calculated using Equation (18) for a fixed time interval of 2.5 s for the reconfiguration. The color scale in Figure 9 shows the higher power required during most of the reconfiguration from one state to another in HTetro-LLL than LLL. The critical cases with the highest power requirement are the transformations from \{J to O\} (14.61 watts), \{Z to O\} (16.51 watts), \{O to S\} (11.42 watts), and \{Z to T\} (10.87 watts) in HTetro-LLL. Similarly, in LLL, the transformation \{L to Z\} and \{T to Z\} showed the highest power required, i.e., 12.46 and 14.90 watts. Therefore, these transformations must be given least priority during the reconfiguration. The joint reaction forces components are also greater for the HTetro-LLR. The net reaction forces or the shaking forces will result in the overall system movement during reconfiguration, as the omni-wheels were used that has passive barrels as shown in Figure 4c. To avoid this, the mass of block #2 was kept high to increase traction forces. To minimize the shaking forces and moments at hinge joints during the reconfiguration the center of mass of each block should be kept nearer to its hinge joint as dealt in [21,22]. The optimal distribution of mass in each block to minimize the shaking forces and moments will be of interest to study in future.

![Figure 9. Power consumption during reconfiguration in simulation from one finite state to another in HTetro-LLL and HTetro-LLR.](image)

5. Experiments

The dynamic modeling in the simulation was used to theoretically calculate the energy consumption of the HTetro during the different reconfigurations. In this section, the experiments were performed on the physical prototypes of the platform to validate the model and simulation results. We have performed, altogether, \(42 \times 2 = 84\) reconfigurations and logged the data for assessing the power consumption during the reconfiguration. In this section, the detailed experimental method and the results are presented along with its discussion.

5.1. Power Consumption Calculation in Experiments

The power consumption is calculated in two steps. First, the energy consumed during the specific time interval is found using the current variation during the reconfiguration. Assuming the power supply to be constant, the expression for the energy in watts/s is

\[
E_i = \int_{t_a}^{t_f} I_i(t)V_i(t)\,dt \equiv V_i \int_{t_a}^{t_f} I(t)\,dt \approx V_i \sum_{t_0}^{t_f} I_i(t)\,dt
\]
The average power during the reconfiguration is then calculated by dividing the energy with the time interval (here for reconfiguration) for the $i$-th joint, as in Equation (21), and then summing for all the joints to get the total power as

$$P_\text{i}(k) = \sum_{i=1}^{n} \left( \frac{E_i}{T_i} \right)$$

(21)

where $T_i$ is the time interval, i.e., the difference between the initial time, $t_0$, and final time, $t_f$, for the reconfiguration, and $E_i$ is the energy consumed for the $i$-th joint. Here also, we have used trapezoidal numerical integration to calculate the energy in Equation (20), as was used with equivalent power calculated in simulation using Equation (18).

5.2. Experimental Set-Up and Data Acquisition

To assess the power consumption during reconfiguration in experiment, the two prototypes, namely, hTetro-LLL and hTetro-LLR, were built as per the mechanical design discussed in Section 2. The servo motor used to drive the hinge joints was “Herkulex DRS 0601” and has the rated stall torque of 6 Nm. It has the maximum rated speed of rotation by 60 degrees per 0.164 s. The quintic trajectory at the joint were provided using the function written in the program for the reconfigurations. To measure the current consumed by servomotors at the hinge joints during operation, the current sensors (ACS 715) were connected in series as shown with circuit’s line diagram in Figure 10. The Arduino Mega board was used to command the servo motors for reconfiguration according to the Table 2. In Figure 10, VDD is the voltage across the motor, and the feedback from the motor is transmitted and received with port TXD and RXD, respectively. The joint angular positions and the current values were logged in the PC through USB. Figure 11 shows the variation of hinge joints angular position and current data logged during the reconfiguration.

The time for reconfiguration from one state to another was kept constant as 2.5 s throughout the experiment in order to standardize the output. In this way the two platforms power consumption during reconfiguration can be compared under the same conditions, i.e., the angular velocity and acceleration profile remains same for the same hinge joint trajectory variations. The power calculated using method discussed earlier for all the reconfigurations are listed in matrix form in the Figure 12. Figure 11a,b shows the current demand during the reconfiguration from {I to T} and {T to I} as 11.71 and 13.16 watts respectively. Unlike the power calculated in simulation (Figure 9), power consumption in experiment from {I to T} and {T to I} differs. The probable reason for this behavior is the friction acting during the joint rotation while reconfiguration. The discussion on the experimental results are done next.

Figure 10. Circuit diagram for logging the current. Experimental steps with video for it can be found at [26].
5.3. Discussion on Experimental Results

It is evident from the observed experimental results both hTetro-LLL and LLR showed interesting behaviour during reconfiguration which is discussed in this section. During the reconfiguration, the combination of hinge joint movement occurred, i.e., only with one joint, two joints and all the three joints involved. The observations made during the reconfigurations are discussed in this section with special reconfiguration cases where the collision among the links during reconfiguration was observed.

The reaction force at the hinge joints is not measured in experiments as the force sensor at the hinge joints is not mounted. The effect of the reaction forces as calculated in the simulation were observed in experiments. The net reaction forces resulted in the movement of the platform as it is free to move about the passive omni-wheels barrels as shown in Figure 4c. During the experiments, more resulting motion due to the net joint reaction forces was observed in hTetro-LLL than hTetro-LLR. The reason can be physically interpreted with hTetro-LLL having its hinge joints all located at one side of the platform makes it more unstable in the presence of joint reaction forces than hTetro-LLR.

The hinge motors actuation time was kept constant at 2500 milliseconds during the reconfigurations, as in the simulation. The increase or decrease in time will influence the acceleration of block and angular velocity during reconfiguration, which, in turn, influence the current profile during the reconfiguration of hinge motors. Figure 12 shows that the power consumption for hTetro-LLL and
LLR are approximately the same for \{L to S\} and \{Z to J\}, as only the second hinge joint needs to be actuated with the same magnitude, i.e., by 90°. The average power consumption by second hinge motor was 5.47 watts, and the total, i.e., the sum of all the joints was 6.13 watts. There is variation in the magnitude in power required moving from \{Z to J\} and while returning, i.e., \{J to Z\}, due to the friction and other mechanical losses apart from the sensor noise. The standard deviation in the readings taken by repeated experiment by moving a single joint was 0.17 watts in terms of power.

The transformation involving three joints movement will have higher power consumption, and it also depends upon the initial and final state to be achieved. For example, the transformation from \{I to T\} in hTetrol-LLL and LLR consumes 11.71 and 12.34 watts, respectively. From the Figure 12, it was observed the power consumption for transformation involving three joints movement are generally higher than 10 watts.

The transformation from \{T to Z\} engages two joints in hTetrol-LLL and LLR. Figure 13a,b shows the reconfiguration of the two platforms. The reconfiguration from \{T to Z\} in hTetrol-LLL consumes 7.79 watts, whereas in hTetrol-LLL, an interesting observation is made: In hTetrol-LLL, for state \{T\}, the shape locking condition for #1 exists due to the position of #4. This is due to the overlapping region during the circular movement of the #1 edge with the #4. This resulted in the locking position. The collision of #1 with the block #4 can be observed in the Figure 13d where the wavy angle variation is encircled and correspondingly peaks in the current data were also observed that goes as high as 4 amperes. This collision is not favorable for the motors and bearings, and it may also cause the motor to burn. To avoid this, the #4 was moved first by 60°, and then the other joints were moved, and the angle and current variations are plotted in Figure 13e. The power consumption for the transformation from \{T to Z\} for hTetrol-LLL is 16.69 watts. The peak current observation will be utilized for the passive compliance of the joints by joint current limiting approach [28]. The schematic of the current limiting approach is shown in Figure 14 for making the hinge joint compliant in case of obstruction during the reconfiguration. This will further make the cleaning robot safer during interaction with human and environment while reconfiguration without any additional sensors.

![Figure 13](image-url)

**Figure 13.** Reconfiguration during T to Z for hTetrol-LLL and LLR. The experimental video referred in [26].
6. Conclusions

In this paper, the assessment of the two architectures of hTetro under two different hinge positions, namely, LLL and LLR, are presented using kinematics and dynamics analysis. The workspace of these platforms was calculated using the graphical approach, i.e., by counting the equivalent number of pixels of the covered area by the shape of each block during rotation. In the simulation, the dynamic modeling using Newton–Euler was done to estimate the joint torques and the forces developed at hinge joints during the reconfiguration. The power due to the constraint forces is zero. Therefore, the power consumption only due to the torque required during reconfiguration for a given quintic trajectory was estimated. We compared the simulation and experimental results utilizing the equivalent mechanical and electrical definition of power. Unlike in the experiments, the power consumption during reconfiguration in simulation from state \( i \) to \( j \) is equal to \( j \) to \( i \), where \( i, j \equiv \{I, J, L, O, S, T, Z\} \). The simulation results reflect similar trends to that of the experiments. The variations between the simulation and experimental results are because of the difference in CAD model properties taken for simulation and the assembled robot, the trajectory input and execution, electrical and mechanical efficiencies of the actuators, etc. This requires system identification to be done for accurate modeling of the assembled robot which is to be carried out in the future.

From experimental results, the hTetro-LLL resulted in comparatively lower power consumption than hTetro-LLR. The reconfiguration matrix gives an idea about power consumption during each reconfiguration, and its usefulness is depicted with the control architecture, where the matrix is used to decide on the reconfiguration based on energy consumption. Therefore, planning of reconfiguration during the area coverage can be achieved by minimizing the power consumption. The ongoing efforts of our team included the modeling and control of mobility and reconfigurability and the dynamic identification of the system. The designing of a docking mechanism for autonomous attachment of two or more architectures of hTetros, along with the development of algorithms for its programmable assembly, are also being explored.

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