A host–parasite structural analysis of industrial robots

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Abstract
Most driving torques in serial industrial robots are used to overcome the weight of the robot. Although actuators account for a large proportion of the total mass of a robot, they have yet to become a positive factor that enables the robot to achieve gravity balance. This study presents a host–parasite structure to reconstruct the distribution of actuators and achieve gravity balance in robots. First, based on the characteristics of tree–rattan mechanisms, a method for calculating the degrees of freedom and a symbolic representation method for the distribution of branched chains are formulated for host–parasite mechanisms. Second, a configuration analysis and optimization method for host–parasite structure-based robots and a robot prototype are presented. Finally, four host–parasite mechanisms/robots (A, B, C, and D) are compared. The results are as follows. If more parasitic branched chains are added to the yz plane, the loads along axes 2 and 3 become more balanced, which significantly increases the stiffnesses of the mechanism in the y- and z-directions (Ky and Kz, respectively). If the additional branched chains are closer to the site of maximum deformation, the stiffness of the mechanism in the z-direction (Kz) increases more significantly. Of the four mechanisms, mechanism D has the best overall performance. The joint torques of mechanism D along axes 2 and 3 are lower than those of mechanism A by 99.78% and 99.18%, respectively. In addition, Kx, Ky, and Kz of mechanism D are 100.56%, 336.19%, and 385.02% of those of mechanism A, respectively. Moreover, the first-order natural frequency of mechanism D is 135.94% of that of mechanism A. Host–parasitic structure is conducive to improving the performance of industrial robots.

Keywords
Multi-loop mechanism, degree of freedom, host–parasite, palletizing robot, structural optimization

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Introduction
Serial robots—robots consisting mainly of serial mechanisms—have a wide range of industrial applications, such as handling, painting, welding, and assembly.1 In a serial robot, an arm actuated by a joint acts like a cantilever beam in which the arm’s center of gravity is not aligned with the axis of the joint. Moreover, most of the joint actuation force is consumed in counteracting the moment resulting from the eccentric weight of the electric motors, gearboxes, and arms. Gravity balancing is critical for resolving such
problems with robots. The major methods for gravity balancing serial and parallel robots use springs, balancing mechanisms, and counterweights. Liu et al. used counterweights and springs in the static balancing of a parallel mechanism with six degrees of freedom (DOFs). Zhang and Wei used a dynamic-balancing mechanism for parallel manipulators. Baradat et al. realized the gravity balance of a Stewart platform and a Delta robot using a scissor mechanism. Yuan et al. proposed a 6UPS-3UPS/UPTU-R (universal-prismatic-spherical joints/universal-prismatic-universal-revolute joints) parallel mechanism and realized the gravity balance of a load through inner-layer balancing of the parallel mechanism. Zhao et al. realized the gravity balance of parallel robots in the entire working envelope by designing an inner-layer-balancing mechanism with a constant Jacobian matrix. Newman and Hogan realized the gravity balance of two-DOF serial robots using a parallelogram-based counterweight. In an attempt to gravity balance Scara-like robots using counterweights or springs, Bruzzone and Bozzini found that the counterweight method was more efficient for low-speed motion, whereas the spring method was preferable for high-speed motion. Agrawal and Fat-tah proposed a theory for gravity balancing of spatial serial robots using springs and auxiliary parallelograms. Gupta et al. optimized the distribution of masses to reduce the driving torques and forces at the joints of a serial robot. Lee et al. used a combination of a cam mechanism and a compression spring to compensate for the gravity torque of the target structure to improve energy efficiency. Feng et al. proposed a new balancing mechanism for industrial robots based on elastic actuators in series. Richiedei and Trevisani studied the relation between spring design and electric energy consumption in a spring balance system. Kim et al. proposed a gravity compensator that can adjust the compensation torque in the roll direction using a reduction gearbox and wire cable.

The structural synthesis of multi-loop mechanisms is fundamental to the gravity balancing of robots. Huang and Zheng divided a multi-loop mechanism into independent groups (loops of branched chains) according to the closing sequence of the groups. On this basis, they investigated the overconstraint of the sequential groups using screw theory and calculated the DOF of the entire multi-loop coupled mechanism based on the overconstraint. Liu et al. calculated the DOF of multi-loop mechanisms by dividing them into equivalent parallel mechanisms. Li et al. analyzed multi-loop mechanisms by combining biological and screw theories. Zhang et al. proposed a new method for synthesizing multi-loop mechanisms based on virtual-loop theory and the Assur group. Zhang et al. transformed the synthesis of multi-loop mechanisms into that of corresponding serial and parallel mechanisms according to typological split and DOF split principles. Hu et al. analyzed multi-loop mechanisms by combining topology with screw theory. Xun et al. proposed a novel rhombohedral three-DOF multi-loop mechanism. Ding et al. proposed a general method for the structural synthesis of two-layer two-loop mechanisms. Wang et al. carried out a kinematic analysis of the 2UPR-2RPU parallel mechanism, which is also a multi-loop mechanism. Chen and Sun built a dynamic model of a multi-ring mechanism with multispherical joint clearances.

In summary, research progress has been made in (1) the gravity balancing of robots and (2) multi-loop mechanisms. However, the gravity balancing of serial robots with two or more DOFs remains a challenge, the theoretical understanding of multi-loop mechanisms remains limited, and there has been insufficient research into the structural optimization of multi-loop mechanisms. In the present study, based on an analysis of tree–rattan mechanisms, a numerical model is established for calculating the DOF of host–parasite (H-P) mechanisms and a method is proposed for their symbolic representation. Then, the structural characteristics of multi-loop mechanisms are analyzed by considering them as H-P mechanisms, and this method is used to optimize the structure of palletizing robots with the aim of gravity balancing their main joints. In particular, the method can be used to improve the energy efficiency and usability of industrial robots.

Analysis of the DOF of a tree–rattan mechanism

Passive DOFs

The DOF of spatial mechanisms can be expressed generally as follows:

$$F = 6(n - g - 1) + \sum_{j=1}^{g} f_j + \mu$$  \hspace{1cm} (1)

where $n$ is the number of links, $g$ is the number of motion joints, $f_j$ is the DOF of the $j$th motion joint, and $\mu$ is the number of overconstraints of the mechanism and is given by

$$\mu = \nu - \lambda(n - g - 1)$$  \hspace{1cm} (2)

where $\lambda$ is the number of general constraints and $\nu$ is the number of redundant constraints (virtual constraints).

When the output link is a widely known and generally recognized output motion platform, the DOF of the output link of a mechanism is also referred to as its nominal DOF ($F_H$). For a mechanism with a passive DOF ($F_P$) that does not affect the DOF of the output link (such as the roller cam mechanism shown in Figure 1), the nominal DOF can be expressed as follows

$$F_H = F - F_P$$  \hspace{1cm} (3)

Equation (3) can be rewritten as follows:

$$F = F_H + F_P$$  \hspace{1cm} (4)
Typology of branched chains of a multi-loop mechanism

A multi-loop mechanism is a type of closed-loop mechanism. Figure 2 shows four different multi-loop mechanisms, where $C_i$ denotes loops that are closed in sequence. A serial kinematic mechanism (SKM) consists of several serially connected self-closed loops. A parallel kinematic mechanism (PKM) consists of several parallel-connected loops that are closed to the frame synchronously. A multi-subloop kinematic mechanism (LKM) consists of several loops that are stacked and closed in sequence, and a multichain kinematic mechanism (CKM) consists of several chains that are stacked and closed in sequence. Many more multi-loop mechanisms can be constructed by combining these four types of mechanism as branched chains in different ways.

An SKM is a special multi-loop mechanism that has closed loops. The loops of a serial mechanism are self-closed. That is, a motion joint and link together form a closed loop. For a self-closed loop of a serial mechanism, a zero-DOF two-arm branched-chain can be connected in parallel to each end of the link to form a triangular-loop serial mechanism, but without adding the DOF of the original mechanism, as shown in Figure 3. The triangular-loop serial mechanism has the following parametric values: $n_1 = 10$, $g_1 = 12$, $v_1 = 0$, and $\lambda_1 = 3$. Substituting these values into Eqs. (1) and (2), its DOF can be calculated as follows:

$$\mu = 0 - 3 \times (10 - 11 - 1) = 6$$

$$F_3 = 6 \times (10 - 11 - 1) + 11 + 6 = 5$$

A tree mechanism has the following parametric values: $n = 3$, $g = 2$, $v = 0$, and $\lambda = 3$. Similarly, substituting these values into Eqs. (1) and (2), its DOF can be calculated as follows:

$$\mu = 0 - 3 \times (3 - 2 - 1) = 0$$

$$F_1 = 6 \times (3 - 2 - 1) + 2 + 0 = 5$$

A rattan mechanism consists of two serially connected branched chains, namely a CKM and an SKM. Because the loop self-closing of serially connected branched chains does not produce an overconstraint, a rattan mechanism can be considered as a single unit in a DOF analysis. Note that in calculating the DOF of a tree mechanism using Eq. (1), the ground must be considered as a link. Similarly, because the DOF of a rattan mechanism depends on the host tree, the entire tree mechanism must be considered as a link of the rattan mechanism. Thus, in calculating the DOF of a rattan mechanism, Eqs. (1) and (2) must be revised as follows:

$$F = 6(n + 1 - g - 1) + \sum_{j=1}^{g} f_j + \mu = 6(n - g) + \sum_{j=1}^{g} f_j + \mu$$

$$\mu = \nu - \lambda(n + 1 - g - 1) = \nu - \lambda(n - g)$$

A rattan mechanism has the following parametric values: $n = 7$, $g = 9$, $v = 0$, and $\lambda = 3$. Substituting these values into Eqs. (5) and (6), its DOF can be calculated as follows:

$$F = 6n + 7(6 - g) + \sum_{j=1}^{g} f_j + \mu$$

$$\mu = 0 - 3 \times (7 - 9) = 6$$

$$F_3 = 6 \times (7 - 9) + 9 + 6 = 3$$

Clearly, $F_3 = F_1 + F_2 = 2 + 3 = 5$, thereby validating Eqs. (5) and (6).

In terms of the relation between the overall DOF and the DOF of the branched chains, a tree–rattan mechanism can be expressed as

$$F^5 = P_{23}^{2}(SKM^2) + P_{25}^{3}(CKM^2 + SKM^1)$$

where $F^5$ is the tree–rattan mechanism and has five DOFs, $P_{23}^{2}(SKM^2)$ is the first branched-chain of the tree–rattan mechanism or the two-DOF tree mechanism, and $P_{25}^{3}(CKM^2 + SKM^1)$ is the second branched-chain of the tree–rattan mechanism or the three-DOF rattan mechanism that consists of a two-DOF CKM and a one-DOF SKM. The DOF of the rattan mechanism does not affect that of the tree mechanism.

Tree–rattan mechanism

Parasitism exists widely in fauna and flora.28,29 A parasitic relationship can be considered as a mechanism in which the host is the output link and the parasite has a passive DOF. Thus, the DOF of a mechanism can be analyzed by considering it as a tree–rattan parasitic relationship or as a tree–rattan mechanism. The tree mechanism can be referred to as the host mechanism, and the rattan mechanism can be referred to as the parasitic mechanism, as shown in Figure 4. The tree–rattan mechanism is a multi-loop mechanism with passive DOF.

Clearly, a tree–rattan mechanism has two branched chains, namely a tree mechanism that is an SKM and a rattan mechanism that is a CKM-SKM hybrid. Tree and rattan mechanisms have overconstraints ($\mu$). For the redundant constraints, $v = 0$ and for the general constraints, $\lambda = 3$ (planar constraints only). A tree–rattan mechanism has the following parametric values: $n = 10$, $g = 11$, $v = 0$, and $\lambda = 3$. Substituting these values into Eqs. (1) and (2), its DOF can be calculated as follows:

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$$F = 6(n + 1 - g - 1) + \sum_{j=1}^{g} f_j + \mu = 6(n - g) + \sum_{j=1}^{g} f_j + \mu$$

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In biology, parasitism is a symbiotic relationship between two species. One species (the parasite) lives in or on another species (the host), preying on it for nutrition and causing it some harm. A tree and a rattan climbing the tree form a biological parasitic relationship, and this parasitism has implications in the theory of mechanisms. The rattan mechanism is parasitic on the tree mechanism through motion joints and benefits from the parasitic relationship. The rattan mechanism has a passive DOF and a parasitic medium, whereas the tree mechanism is constrained by the singularity of the rattan mechanism. A tree–rattan mechanism can also be referred to as an H-P mechanism. The H-P mechanism is a multi-loop mechanism with passive DOF.

A host mechanism has a dependent DOF, which can be calculated using

$$ FH = 6(n_H - g_H - 1) + \sum f_H + \mu_H $$ \hspace{1cm} (8)

$$ \mu_H = \nu_H - \lambda_H(n_H - g_H - 1) $$ \hspace{1cm} (9)

whereas a parasitic mechanism is one that relies on a host mechanism to form its own DOF. A parasitic mechanism can serve as a host for another parasitic mechanism. The DOF of a parasitic mechanism can be calculated using

$$ FP = 6(n_P + 1 - g_P - 1) + \sum f_P + \mu_P = 6(n_P - g_P) $$

$$ + \sum f_P + \mu_P $$ \hspace{1cm} (10)

$$ \mu_P = \nu_P - \lambda_P(n_P + 1 - g_P - 1) = \nu_P - \lambda_P(n_P - g_P) $$ \hspace{1cm} (11)

where 1 in $n_P + 1$ indicates that the host is considered as a link of the parasitic mechanism. Note that this consideration is critical to the correct calculation of the DOF of the parasitic mechanism.

A mechanism formed by combining host and parasitic mechanisms is a hybrid mechanism and is referred to as an H-P mechanism. The overall DOF of an H-P mechanism can be expressed as follows

$$ F_{HP} = F_H + \sum F_P \quad (F_H \geq 0, F_P \geq 0) $$ \hspace{1cm} (12)

Thus, Eqs. (8)–(12) constitute a numerical model for calculating the DOF of H-P mechanisms. As shown above, the branched chains of mechanisms can be classified into four types, namely SKM, PKM, LKM, and CKM. An H-P mechanism formed by a combination of these four different mechanisms can be expressed as follows

**Structural analysis of the H-P mechanism**

**H-P mechanism**

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where $F^z$ is the mechanism with an overall DOF of $Z$ and $P_{pi}^i$ is the $i$th branched-chain of the mechanism with a passive DOF of $P_i$, which can be an SKM with a DOF of $P_1$, a PKM with a DOF of $P_2$, an LKM with a DOF of $P_3$, or a CKM with a DOF of $P_4$. Note that $P_1 + P_2 + P_3 + P_4 = P_{pi}$ and $\sum P_i = Z$. The model can be used to analyze the underlying DOF formation process of H-P mechanisms.

Characteristics of different parasitism modes
The basic parasitism modes include parasitism on a joint, on a link, and on both a joint and a link, as shown in Figure 5. Parasitic branched chains of mechanisms can be formed by combining these three parasitism modes. According to the relationship between parasitic branched chains and that between parasitic and host branched chains, the following modes of the parasitism of branched chains can be identified in H-P mechanisms: climbing, parallel, serial, stacking, splitting, and symbiotic parasitism. Table 1 compares the different parasitism modes.

Optimization and case analyses
Palletizing robots: Problems and optimization objective
The main functions of a palletizing robot are gripping, transporting, and stacking objects. A palletizing robot may have a serial or semiserial structure, as shown in Figure 7. A six-DOF serial robot has six actuators ($D_1$–$D_6$), while a four-DOF semiserial robot has four actuators ($D_1$–$D_4$). When gripping, placing, or waiting, a palletizing robot must hover for different durations. Because of the constraints of the structural design, the robot has an eccentric center of mass. Thus, the actuators must output torque even when the robot hovers, and the control system must be robust enough to ensure that the robot can hover stably. Moreover, the electric motors and gearboxes account for 40–60% of the total mass of the robot. Thus, the robot has low mechanical efficiency and positioning accuracy and is prone to residual vibrations, all of which increase the difficulty of system control.

Thus, the following optimization objectives were defined for palletizing robots: (1) the robot must be able to maintain the static balance of its main joints, (2) the robot must be able to maintain the center of mass of its moving links constant in any pose at any position in its working envelope, and (3) the robot must require only a minimal counterweight for gravity balance.
Structural optimization steps

The structural optimization of a robot is gradually achieved by comparing the advantages and disadvantages of the parasitic branched chains in various optimized schemes. The symbolic representation method (Eq. (13)) for mechanisms aims to establish corresponding relationships between sub-DOFs and specific parasitic branched-chain types, while ensuring that the total number of DOFs remains unchanged in the various optimized schemes. The structure of an H-P mechanism can be optimized through the steps listed in Figure 8.

Step 1: Define the objective of the optimization: The problems with the target mechanism are analyzed and the objective of the optimization and the relevant constraints are defined.

Step 2: Analyze the DOF and the branched-chain combination of the target mechanism and identify the root causes of the problems.

Step 3: Ensure that there is no change in the total number of DOFs. This is the main constraint in structural optimization when using a symbolic representation method. Let $F^Z$ be a mechanism where $Z$ is the total number of DOFs. After decomposing the DOFs of $F^Z$, $P_i\, i$ is used to represent the mechanism’s branched-chain $S_i$, which has $P_i$ sub-DOFs ($\sum P_i = Z$). A preliminary optimized configuration is designed based on the optimization objective. $S_i$ can be any combination of SKMs, PKMs, LKMs, and CKMs. Several design combinations that can be represented by symbols can be obtained based on the selectable combinations of DOFs and branched chains.

Step 4: Reorganize the order of design schemes: to save a lot of optimization calculation time, optimization is performed in a progressive manner. The multiple configuration schemes obtained by type synthesis are sorted according to the number of parasitic branches. For example, first, the host mechanism without parasitic branch chain, then the configuration with only one parasitic branch chain, and then the configuration with multiple branches.

Step 5: Select a parasitism mode: The design options output from step 3 are analyzed, and a parasitism mode is selected based on the optimization objective and the characteristics of the available parasitism modes (Table 1).

Step 6: Assess whether the constraints for the optimization objective have been met. If not, go back to step 4 and look for other optimized schemes.

Step 7: Select an optimization option, undertake the dimensional design of a prototype, and fabricate and validate the prototype.
In a serial robot, an arm actuated by a joint acts like a cantilever beam, with the arm’s center of gravity not aligned with the axis of the joint. Moreover, most of the joint actuation force is consumed in counteracting the moment resulting from the eccentric gravity of the electric motors, gearboxes, and arms.
Similarly, the following expression can be derived from Eq. (13) to represent a four-DOF semiserial robot

$$F^4 = P_{s1}^{l}(SKM^1) + P_{s2}^{l}(LKM^1) + P_{s3}^{0}(CKM^0) + P_{s4}^{l}(SKM^1)$$  \hspace{1cm} (15)$$

A semiserial robot has the characteristics of an H-P mechanism. The branched-chain $P_{s2}^{l}(SKM^2)$ is the host mechanism and consists of two-DOF SKMs. There are three parasitic branched chains, namely $P_{s1}^{l}(LKM^1)$, $P_{s3}^{0}(CKM^0)$, and $P_{s4}^{l}(SKM^1)$. $P_{s2}^{l}(LKM^1)$ and $P_{s3}^{0}(SKM^2)$ enable the robot to translate in the $X$-, $Y$-, and $Z$-directions. $P_{s1}^{l}(SKM^2)$ has a passive DOF of zero, which enables the output link to maintain a horizontal pose. $P_{s3}^{0}(SKM^1)$ enables the output link to rotate in the $Z$-direction. For a semiserial robot, most of the actuators can be placed near the frame to reduce the eccentric load on the joints, but a static balance of the main joints cannot be realized.

**Structural optimization**

**Breaking down the DOF**

1) A semiserial robot can perform most palletizing and handling operations but has a lower eccentric load than a serial robot. Thus, a semiserial robot was selected for further optimization by breaking down the DOF of the host mechanism. Thus, the following expression can be derived from Eq. (13)

$$F^4 = P_{s1}^{l}(SKM^1) + P_{s2}^{l}(SKM^1) + P_{s3}^{0}(LKM^1) + P_{s4}^{l}(SKM^1)$$  \hspace{1cm} (16)$$

**Changing the cantilever arms to balanced long branched chains**

2) Both LKMs and CKMs can serve as long branched chains, but a CKM is a better option for a passive DOF of the far-end output link. Thus, $P_{s3}^{0}(CKM^0)$ was retained without change, whereas $P_{s4}^{l}(SKM^1)$ was changed to $P_{s3}^{l}(CKM^1)$. Both LKMs and CKMs can be used to realize a passive DOF near the frame, so the following branched-chain combinations are available

$$V_1 = F^4 = P_{s1}^{l}(CKM^1) + P_{s2}^{l}(CKM^1) + P_{s3}^{l}(LKM^1) + P_{s4}^{l}(SKM^1)$$  \hspace{1cm} (17)$$

$$V_2 = F^4 = P_{s1}^{l}(LKM^1) + P_{s2}^{l}(LKM^1) + P_{s3}^{l}(LKM^1) + P_{s4}^{l}(CKM^0)$$  \hspace{1cm} (18)$$

$$V_3 = F^4 = P_{s1}^{l}(LKM^1) + P_{s2}^{l}(LKM^1) + P_{s3}^{l}(LKM^1) + P_{s4}^{0}(CKM^0)$$  \hspace{1cm} (19)$$

$$V_4 = F^4 = P_{s1}^{l}(LKM^1) + P_{s2}^{l}(LKM^1) + P_{s3}^{l}(LKM^1) + P_{s4}^{0}(CKM^0)$$  \hspace{1cm} (20)$$

The static balance of the robot structure was optimized. The four DOFs correspond to the four main joints on axes 1–4, namely $G_1$–$G_4$, as shown in Figures 8 and 9. $G_1$ of axis 1 of the base and $G_4$ of axis 4 of the output link are rotations in the vertical direction. Because the load on axis 1 was markedly larger than that on axis 4, priority was given to balancing the load on axis 1 by aligning the overall center of mass of the robot with axis 1. $G_2$ of axis 2 and $G_3$ of axis 3 are rotations in the vertical plane and thus required gravity balancing. For gravity balancing of $G_2$ of axis 2, because the eccentric load was on the left side of the joint, all the branched chains were extended to the right side of joint $G_2$ and all the actuators of the branched chains were installed on the right side of the joint. In other words, leverage was used, with the joint serving as the fulcrum of the lever. Similarly, for the gravity balancing of $G_3$ of axis 3, all the actuators were installed on the right side of the joint.

**Selecting an appropriate parasitism mode**

3) Four optimization options ($V_1$–$V_4$) were analyzed. Climbing parasitism was adopted for long branched chains using CKMs. Because there were
The major differences between the four optimization options are in branched chains $P_{S1}$ and $P_{S2}$. For branched-chain $P_{S1}$, to utilize fully the large weight of axis 1, its actuator was moved near to axis 2. Because of the large movement required, LKM was not feasible. Thus, CKM was adopted and incorporated through climbing parasitism. For branched-chain $P_{S2}$, the actuator was also moved near to axis 2 but only by a small distance. Both LKM and CKM were feasible options for $P_{S2}$, but LKM was simpler. Table 2 compares the parasitism modes and the advantages and disadvantages of the four optimization options. The final option selected was $V_3$.

To further move the axis-1 actuator (which has already been moved to near axis 2) to the balanced side of axis 2, a zero-DOF branched-chain, LKM$_0$, was added to branched-chain $P_{S1}$. Figure 9 shows the final design of the H-P structure of the palletizing robot. Branched-chain LKM$_0$ is highlighted in green. The optimized structure can then be expressed as follows

$$V_3 = F^4 = P_{s1}^1(CKM^1 + LKM^0) + P_{s2}^1(LKM^1) + P_{s3}^1(LKM^1) + P_{s4}^0(CKM^0) + P_{s5}^1(CKM^1)$$

(21)

Table 3 presents the calculation of the DOF of the branched chains of the palletizing robot. The overall DOF of the optimized robot was $F = 1 + 0 + 1 + 1 + 0 + 1 = 4$.

Selecting an optimization option and fabricating prototypes

4) Based on the optimized structural design, a dimensional design was completed and a prototype H-P palletizing robot was fabricated, as shown in Figure 10. The final design of the robot had four main joints, namely $G_{1}$-$G_{4}$, and four actuators, namely $D_{1}$-$D_{4}$. A patent for the invention has been filed.

Analyzing operating performance

5) In the new design of the palletizing robot, all the electric motors and gearboxes as well as a small fraction of the counterweight were concentrated on the right side of $G_2$. None of the servomotors had a brake. The payload (10 kg) held by the robot gripper can be moved manually to any position in the working envelope and can hover for a long time without the actuators outputting torque. Because the actuators do not need to output torque when the new robot hovers at any position in the working envelope, the mechanical efficiency has also improved (by different degrees under different operating conditions). Table 4 compares the operating performance of the serial, semiserial, and H-P palletizing robots.

Comparative analysis of H-P structures of robots

Four configurations in the formation of a new H-P mechanism

To facilitate a unified comparative analysis, four mechanisms, A, B, C, and D, were designed using the process for creating a robot prototype. Each of the four mechanisms is set to the attitude in which the manipulator extends the furthest working distance, as shown in Figure 11. Each mechanism has four DOFs (achieved jointly by axes 1, 2, 3, and 4), corresponding to the main joints $G_1$, $G_2$, $G_3$, and $G_4$ as well as actuators $D_1$, $D_2$, $D_3$, and $D_4$, respectively.

Mechanism A is a serial mechanism with no parasitic branched chains and can serve as a host mechanism, as shown in Figure 11(a). Mechanism B is formed by adding a balancing parasitic branched-chain and a parasitic branched-chain along axis 3 to mechanism A as well as moving actuator $D_3$ of mechanism A at joint $G_3$ to the right of joint $G_2$, as shown in Figure 11(b). Mechanism C is formed by moving actuator $D_1$ of mechanism B at joint $G_1$ to the right of joint $G_2$ via the parasitic branched-chain along axis 1 as well as moving actuator $D_2$ of mechanism B at joint $G_2$ to the right of joint $G_2$ via the parasitic branched-chain along axis 2, as shown in Figure 11(c). Mechanism D is formed by moving actuator $D_4$ of mechanism C at joint $G_4$ to the right of joint $G_2$ via the parasitic branched-chain along axis 4, as shown in Figure 11(d).

The position of the center of mass and joint torque

Figure 12 shows a Cartesian coordinate system $xyz$ for the robots. The $y$- and $x$-axes coincide with axes 1 and 2,
respectively. The point of intersection of axis 1 and the ground is the origin of the coordinate system, O. The mass of each component of each robot is simplified as a mass point \( m_i \). Let \( \mathbf{r}_i \) be the spatial location of each mass point. Let \( M \) be the overall mass of the whole robot composed of \( N \) components

\[
M = \sum_{i=1}^{N} m_i \quad (22)
\]

Let \( M_0 \) be the mass of the system of mass points of the base. Let \( M_{G1}, M_{G2}, M_{G3}, \) and \( M_{G4} \) be the masses of the systems of mass points that rotate relative to axes 1, 2, 3, and 4, respectively. The judgment method is as follows: for example, consolidate axes 2, 3, and 4, rotate axis 1, and observe which robot parts rotate around axis 1. Then

\[
M = M_0 + M_{G1} \quad (23)
\]

The position of the center of mass (\( \mathbf{r}_c \)) of a whole robot is

\[
\mathbf{r}_c = \frac{\sum_{i=1}^{N} m_i \mathbf{r}_i}{\sum_{i=1}^{N} m_i} = \frac{\sum_{i=1}^{N} m_i \mathbf{r}_i}{M} \quad (24)
\]

The components of the above equation are as follows
Table 4. Operating performance of palletizing robots with different structural designs.

| Serial number design | Static Gravity compensation | Kinematic solution (branch-chain) | Dynamic performance | Control-system robustness | Requirements for mechanical efficiency | Mechanical cost |
|----------------------|-----------------------------|----------------------------------|---------------------|----------------------------|----------------------------------------|----------------|
| 1                    | Serial                      | SKM                             | High                | Average                    | Average                                | High          |
| 2                    | Semi-serial                 | No SKM                          | High                | Average                    | Low                                    | Low           |
| 3                    | H-P                         | No SKM                          | Low                 | Average                    | Good                                   | Low           |

| Serial number design | Static Gravity compensation | Kinematic solution (branch-chain) | Dynamic performance | Control-system robustness | Requirements for mechanical efficiency | Mechanical cost |
|----------------------|-----------------------------|----------------------------------|---------------------|----------------------------|----------------------------------------|----------------|
| 1                    | Serial                      | SKM                             | High                | Average                    | Average                                | High          |
| 2                    | Semi-serial                 | No SKM                          | High                | Average                    | Low                                    | Low           |
| 3                    | H-P                         | No SKM                          | Low                 | Average                    | Good                                   | Low           |

The positions of the centers of mass of each of the systems of mass points with masses $M_{G1}$, $M_{G2}$, $M_{G3}$, and $M_{G4}$, respectively, are as follows

\[
x_c = \frac{\sum m_i x_i}{M}, \quad y_c = \frac{\sum m_i y_i}{M}, \quad z_c = \frac{\sum m_i z_i}{M}
\]  

(25)

Let $z_2$ and $z_3$ be the positions of axes 2 and 3 in the z-direction, respectively. To facilitate the comparison of the changes in the position of the center of mass in the z-direction relative to axes 2 and 3, $Z_{G2-2}$ and $Z_{G3-3}$ are defined as follows

\[
Z_{G2-2} = |z_{G2} - z_2|
\]  

(30)

\[
Z_{G3-3} = |z_{G3} - z_3|
\]  

(31)

To analyze the relationship between the mass of the actuators and the mass of all the movable robot components ($M_{G1}$), the same type of actuator is used in all four mechanisms. Let $M_{4D}$ be the mass of the system of mass points composed of actuators $D_1$, $D_2$, $D_3$, and $D_4$. Let $P$ be the ratio of $M_{4D}$ to $M_{G1}$

\[
P = \frac{100M_{4D}}{M}
\]  

(32)

Here, only the gravitational effect $g$ is taken into consideration. Let $T_{G2}$ and $T_{G3}$ be the rotational torques of the systems of mass points with masses $M_{G2}$ and $M_{G3}$ relative to axes 2 and 3, respectively. Then

\[
T_{G2} = \sum g m_{G2(i)} |z_{G2(i)} - z_2| = g M_{G2} \sum m_{G2(i)} |z_{G2(i)} - z_2| = g M_{G2} z_{G2-2}
\]  

(33)
**Figure 11.** H-P mechanisms/robots with various configurations. (a) Mechanism A, (b) mechanism B, (c) mechanism C, and (d) mechanism D. H-P: host–parasite.

**Figure 12.** Deformation of various robots in the \( x \)-direction under the external load \( F_{e1} \). (a) Mechanism A, (b) mechanism B, (c) mechanism C, and (d) mechanism D.
\[ T_{G3} = \sum g m_{G3(i)} |z_{G2(i)} - z_3| \]
\[ = gM_{G3} \sum m_{G3(i)} |z_{G3(i)} - z_3| = gM_{G3}z_{G3-3} \] (34)

In this study, the mass and position of the center of mass of each component of each robot were determined based on its three-dimensional (3D) model. In addition, the following parameters were also obtained: \( z_2 = 0.00000 \text{ m} \), \( z_3 = 0.72582 \text{ m} \), and \( M_{G4} = 78.054 \text{ kg} \). Table 5 summarizes the various parameter values (such as mass, position of the center of mass, and joint torques) for each robot, which were calculated by substituting the parameter values into Eqs. (22) and (34).

To verify the accuracy of the centroid position model, the starting torque of the 2-axis and 3-axis of the mechanism D measured by the torque sensor is 6.83 Nm and 4.89 Nm, respectively, and the model calculation results are 1.68 Nm and 1.36 Nm. Due to the friction force of the joint bearing and the weight of the torque sensor, the experimental result is larger than the model calculation result. The experimental results are of the same order and close to the model calculation results, so the accuracy of the robot centroid position model is verified.

Here, the data for mechanism A are used as the reference. The parasitic branched chains (excluding the actuators) account for a relatively small proportion of the total mass. Compared to mechanism A, the most significant increase in \( M \) and \( M_{G1} \) was found with mechanism D. Specifically, \( M \) and \( M_{G1} \) of mechanism D are 6.68% and 10.01% higher than those of mechanism A, respectively. The changes to \( M_{G2} \) and \( M_{G3} \) were primarily caused by the relocation of the actuators and the changes in the parasitic branched chains. \( M_{G4} \) is the workload at the end of the robot. The values of \( P \) for the four mechanisms are 42.83%, 40.91%, 40.10%, and 38.93%, respectively. This suggests that the actuators account for a very large proportion of the total mass of the movable robot components.

Mechanism B was formed only by moving actuator \( D_3 \) of mechanism A from joint \( G_3 \) to near joint \( G_2 \). As actuator \( D_3 \) plays no role in balancing joint \( G_3 \), there are no notable differences in \( z_{G2-3} \) and \( T_{G3} \) between mechanisms A and B. However, actuator \( D_3 \) balances joint \( G_2 \). This results in a decrease of \( z_3 \) and \( z_{G2-2} \) to 19.03% and 20.40% of the respective reference values. This suggests that compared to mechanism A, the systems of mass points of mechanism B with masses \( M \) and \( M_{G2} \) are significantly closer to axes 1 and 2 in the \( z \)-direction. This also leads to a decrease in \( T_{G2} \) to 21.33% of the reference value.

Compared to mechanism A, actuator \( D_3 \) of mechanism C is located at an outer position and plays a role in balancing both joints \( G_2 \) and \( G_3 \). In addition, compared to mechanism A, actuators \( D_1 \) and \( D_2 \) of mechanism C are located to the right of joint \( G_2 \) and play a role in balancing joint \( G_2 \). This results in a decrease in \( z_3 \), \( z_{G2-2} \), and \( z_{G3-3} \) to 4.30%, 5.83%, and 7.64% of the respective reference values.

| Case | \( M \) (kg) | \( M_{G1} \) (kg) | \( M_{G2} \) (kg) | \( M_{G3} \) (kg) | \( M_{G4} \) (kg) | \( p \) (%) | \( z_3 \) (m) | \( z_{G2-2} \) (m) | \( T_{G2} \) (N·m) | \( T_{G3} \) (N·m) |
|------|--------------|----------------|----------------|----------------|----------------|--------|-------------|-------------|---------------|---------------|
| A    | Case 1       | 228.093 182.522 | 121.155 72.281 | 23.281 10.027 | 10.017 42.83 | 0.05536 | 0.68275 | 0.33712 | 0.64954 | 0.73066 |
|      | Case 2       | 233.622 190.781 | 126.684 75.954 | 23.896 10.027 | 10.027 40.91 | -0.057 0.53875 | 0.30414 | 0.13246 | 0.64484 | 0.713001 |
|      | Case 3       | 233.516 194.675 | 146.311 79.545 | 79.545 10.027 | 10.027 40.91 | -0.059 0.56373 | 0.64594 | 0.13246 | 0.65883 | 0.713001 |
|      | Case 4       | 243.327 200.487 | 152.537 80.356 | 80.356 10.027 | 10.027 40.91 | -0.061 0.56699 | 0.69454 | 0.13246 | 0.68935 | 0.713001 |

Table 5. Parameter values for each robot.
values. This suggests that compared to mechanism A, the systems of mass points with masses $M_1$, $M_2$, and $M_3$ of mechanism C are significantly closer to axes 1, 2, and 3 in the $z$-direction. This also results in a decrease in $T_{G2}$ and $T_{G3}$ to 7.04% and 26.11% of the respective reference values.

Compared to mechanism A, actuator $D_4$ of mechanism D is also to the right of joint $G_2$ and balances both joints $G_2$ and $G_3$. This results in a decrease in $z_{C_2}$, $z_{G2-2}$, and $z_{G3-3}$ to 2.48%, 0.17%, and 0.236% of the respective reference values. This suggests that compared to mechanism C, the systems of mass points with masses $M_1$, $M_2$, and $M_3$ of mechanism D are even closer to axes 1, 2, and 3 in the $z$-direction. This also results in a decrease in $T_{G2}$ and $T_{G3}$ to 0.22% and 0.82% of the respective reference values. Evidently, gravity balance has basically been achieved in mechanism D along axes 2 and 3.

Comparative analysis of stiffness and mode

In this section, the relationship between translational deformation and external forces (excluding moments) is examined for these four robots. The external load $F_e$ at the end of each robot can be represented by the following matrix

$$F_e = [F_{ex}, F_{ey}, F_{ez}]^T$$

The following equation shows the relationship between $F_e$, the stiffness $K$, and the overall deformation $\delta S_P$ at the end of each robot

$$K = \frac{F_e}{\delta S_P} = [K_x, K_y, K_z]^T$$

where

$$\delta S_P = [\delta S_{P_x}, \delta S_{P_y}, \delta S_{P_z}]^T$$

The 3D robot models were imported into Ansys Workbench for a stiffness and modal analysis. The following boundary conditions were set for each robot. The base was fixed to the ground. A unidirectional external load was applied to the end surface of the flange at the end of the robot. Gravity was taken into account for all components. Meshes were generated for mechanisms A, B, C, and D using the automatic mesh generation technique, which produced a combination of tetrahedrons and hexahedrons. In total, 719,487, 781,413, 1,229,640, and 1,314,024 mesh cells were generated for mechanisms A, B, C, and D, respectively. No-separation contact conditions were applied to the connecting links that move relative to one another at the joints, whereas bonded contact conditions were applied to all other components. The parameters of each robot component were set based on the material used in practice to produce it.
Let $K_x$, $K_y$, and $K_z$ be the $K$ values for each robot in the $x$-, $y$-, and $z$-directions, respectively. An external load was applied to the center of rotation of the end surface of the flange along the negative $x$-direction (Figure 12)

$$F_{e1} = [-100 \text{ N}, 0 \text{ N}, 0 \text{ N}]^T$$  \hspace{1cm} (38)

Figure 12 shows the deformation in the $x$-direction.

An external load along the negative $y$-direction was applied to the end surface of the flange

$$F_{e2} = [0 \text{ N}, -100 \text{ N}, 0 \text{ N}]^T$$  \hspace{1cm} (39)

Figure 13 shows the deformation in the $y$-direction.

An external load along the negative $z$-direction was applied to the end surface of the flange

$$F_{e3} = [0 \text{ N}, 0 \text{ N}, -100 \text{ N}]^T$$  \hspace{1cm} (40)

Figure 14 shows the deformation in the $z$-direction.

As robot links are made mainly of aluminum alloys and the furthest working distance is 1.638 m, the $K$ values of mechanisms A, B, C, and D are relatively low. Table 6 summarizes the maximum deformation $K$ and the natural frequencies of each of the four mechanisms.

To verify the accuracy of the robot stiffness model based on the finite element method, an experimental measurement system for the deformation of the mechanism D is established, as shown in Figure 15. The robot and the lifting jack are fixed to the ground and the wall, respectively, add a force of $-100$ N in the $X$, $Y$, and $Z$ directions of the robot end through the lifting jack, measure the force of the lifting jack loading through the force sensor, and then use a micrometer to measure the deformation of the mechanism D. The stiffness is obtained by conversion from Eq. (36). The experimental results are $K_{x1} = 33$ N/mm, $K_{y1} = 89$ N/mm, and $K_{z1} = 870$ N/mm, and the finite element calculation results are $K_{x2} = 24$ N/mm, $K_{y2} = 88$ N/mm, and $K_{z2} = 558$ N/mm. The maximum deviation between the finite element calculation results and the experimental results is 35.58%. Because the finite element model does not consider the friction force of the joint bearing and the irregular geometry is simplified, the calculation result of the finite element model is smaller than the experimental result. The results of the finite element calculation are the same as and close to the experimental results, so the accuracy of the robot stiffness model is verified.

The data for mechanism A are used as the reference. The $K_x$ values of mechanisms C and D differ relatively insignificantly from that of mechanism A. In contrast, $K_x$
of mechanism B (119.31% of the reference value) is slightly higher than that of mechanism A. This suggests that the added parasitic branched chains exert no significant impact on $K_x$.

The $K_y$ values of mechanisms B, C, and D are significantly higher than the reference value. Specifically, the $K_y$ values of mechanisms B, C, and D are 216.13%, 276.13%, and 336.19% of the reference value, respectively. This suggests that if more parasitic branched chains are added to the $yz$ plane, then the loads along axes 2 and 3 are more balanced and there is a significant increase in $K_y$.

The parasitic branched-chain added to mechanism A to form mechanism B is at the site of the maximum deformation of mechanism A. As a result, the most significant increase in $K_z$ is found in mechanism B. Specifically, $K_z$ of mechanism B is 490.03% of the reference value. In addition, the $K_z$ values of mechanisms C and D are also significantly higher than the reference value (358.48% and 385.02% of the reference value, respectively). This suggests that if the branched chains added to the $yz$ plane are closer to the site of maximum deformation, then the increase in $K_z$ is more significant. Compared to the location where branched chains are added, the extent to which the loads along axes 2 and 3 are balanced has a secondary impact on $K_z$.

Next, we compared the first three orders of the natural frequencies of the mechanisms. Compared to mechanism A, mechanisms B and C each have an additional parasitic branched-chain along axis 3. As a result, the first-order natural frequencies of mechanisms B and C are 118.67% and 118.48% of the reference value, respectively. The effects of the parasitic branched chains along axes 1 and 2 are insignificant. Compared to mechanisms B and C, mechanism D has a parasitic branched-chain along axis 4. This leads to a further increase in the first-order natural frequency to 135.94% of the reference value. For the four mechanisms, as the number of parasitic branched chains increases, there is a decrease in the second-order natural frequency but an increase, to varying degrees, in the third-order natural frequency.

### Conclusions

Serial robot is a widely used industrial robot. The serial robot has the advantage of large working space but also has the disadvantages of low motion accuracy, low rigidity, and low mechanical efficiency. The purpose of this study is to propose a H-P structure to reconstruct the driver

| Percentage of case $i/1$ ($i = 2, 3, 4$) | Case 2/1 | Case 3/1 | Case 4/1 |
|------------------------------------------|----------|----------|----------|
| $\delta S_{px}$ (mm)                     | 83.82    | 94.63    | 99.44    |
| $\delta S_{py}$ (mm)                     | 46.27    | 36.16    | 29.75    |
| $\delta S_{pz}$ (mm)                     | 20.41    | 27.90    | 25.75    |
| $K_x$ (N/mm)                             | 119.31   | 105.67   | 100.56   |
| $K_y$ (N/mm)                             | 216.13   | 276.55   | 336.19   |
| $K_z$ (N/mm)                             | 490.03   | 358.48   | 385.02   |

| The first-order natural frequency (Hz)   | 118.67   | 118.48   | 135.94   |
| The second-order natural frequency (Hz)  | 92.33    | 71.25    | 79.54    |
| The third-order natural frequency (Hz)   | 120.97   | 106.68   | 108.99   |
distribution, achieve the gravity balance of the serial robot, and improve the performance of the robot.

1. This study analyzed the characteristics of tree–rat-tan mechanisms in terms of DOFs and branched chains. We developed an H-P structure with multi-loop mechanisms and formulated a method for calculating DOFs and a symbolic representation method for branched-chain distributions of H-P mechanisms. Based on the H-P structure, the configuration of full- and semiserial palletizing robots was optimized and an innovative design was developed. In addition, new palletizing robot prototypes with a gravity-balancing function were also developed.

2. The H-P structure renders it possible to redistribute the actuators and masses in the robots. \( M_{4D} \) of mechanism A accounts for 42.83\% of its \( M_{G1} \). Three mechanisms, B, C, and D, were formed by moving \( M_{4D} \) as a whole to the balance positions along axes 2 and 3 by way of parasitic branched chains. For mechanisms B, C, and D, the joint torques of mechanism D differ the most significantly from those of mechanism A. Specifically, the joint torques of mechanism D along axes 2 and 3 are 99.78\% and 99.18\% lower than those of mechanism A, respectively. A static balance along axes 2 and 3 was achieved in mechanism D.

3. Adding parasitic branched chains can help improve the \( K \) of robots. If more parasitic branched chains are added to the \( yz \) plane, then the loads along axes 2 and 3 are more balanced and the increase in \( K_y \) and \( K_z \) of the mechanism is more significant. If the additional branched chains are closer to the site of maximum deformation, then the increase in \( K_y \) of the mechanism is more significant. In particular, \( K_x \), \( K_y \), and \( K_z \) of mechanism D are 100.56\%, 336.19\%, and 385.02\% of those of mechanism A, respectively. For the four mechanisms, as the number of parasitic branched chains increased, there was an increase, to varying degrees, in the first- and third-order natural frequencies but a decrease in the second-order natural frequency.

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