Abstract—Dynamic balance has been studied to eliminate the shaking forces and vibration at the base induced by rapid motion of robotic devices. This is done by designing the mass distribution such that the total center of mass of the mechanism is stationary for all motions. However, when the payload changes, for example during pick-and-place action, the dynamic balance cannot be maintained, and vibrations will appear, reducing the accuracy. In this paper, five strategies are described to adapt the dynamic balance under varying payload conditions. Three of these strategies rely on reconfiguration of the mechanism; by changing position the counter weights (I), by changing the joint locations (II) or by altering the amount of counter weight (III). The last two strategies use active control of additional linkages to steer the mechanism in over a reactionless trajectory. These additional linkages can be placed at the base as a reaction mechanism (IV), or within the kinematic chain with redundant joints (V). The implications and differences of these strategies are shown by applying them to a 3 degree of freedom (DOF) planar mechanism. All strategies can provide adaptive dynamic force balance, but have different features, especially added complexity (II & III), reconfiguration force (I & III), or energy consumption (IV & V).

Keywords: adaptive dynamic balance, serial mechanisms, varying payload

I. Introduction

Increasing the throughput and velocities of robotic manipulators amplifies the variation of reaction forces and moments. These changing reaction forces, called shaking forces, result in vibrations of the base and in reduced accuracy of the end-effector. Waiting time has to be introduced to let the vibrations die out, reducing the throughput and efficiency of the mechanism. Dynamic balance is used to minimize or eliminate these shaking forces by design of the mass distribution of the mechanism \cite{1, 2}. However, when the payload of the mechanism changes - for example during pick-and-place applications - an unbalance is induced, leading to reappearing shaking forces and moments. The adaptive dynamic balance is introduced to minimize or eliminate the shaking forces under a varying payload. Shaking forces and moments occur when the momentum of the mechanism changes. When the linear momentum of a mechanism is constant the system is said to be force balanced. When both the forces and moments are constant, the mechanism is called to be dynamically balanced.

Dynamic balance is used to reduce the vibrations, noise, and wear. Other advantages include; energy efficiency due to statically balance, reduced bearing loads \cite{3} and, decoupling of base disturbances.

Adaptive dynamic balancing of manipulators is a relatively new research field. Chung et al. \cite{4} used movable masses to balance a 3-DOF serial robot to eliminate gravity loading. Coelho et al. \cite{5} proposed a similar approach for a 2-DOF manipulator. In \cite{6}, three force balancing approaches are described. The three approaches rely on relocation of the balancing mass, relocation the center of rotation and changing the value of the mass. These strategies are applied to a 1-DOF mechanism. Active balancing mechanisms are proposed to reduce shaking forces and moments by control of a reaction mechanism. For pick-and-place application an active dynamic balanced 2-DOF mechanism has been proposed in \cite{7}. It uses a SCARA type reaction mechanism with a reaction wheel to balance a XY linear actuator. The balancing mechanism can account for a change in payload by increasing the amplitude of reaction motion. Adaptive dynamic balance has been used in rotary mechanism such as turbo engines and CDs \cite{8, 9}. Here the change of mass distribution can be compensated actively or passively. Yoshida et al. \cite{10} used a kinematic redundant arm for operation in space. The redundancy was used to steer the arm over a reactionless trajectory such that the base, in this case the satellite was not disturbed by the reaction forces of the manipulator. Adaptive static balance has already been used \cite{11} for energy free reconfiguration.

In the recent years parallel manipulators have gained a lot of attention. The Delta robot has been implemented into a wide variety of industries, including pick-and-place as well as rapid prototyping. Parallel manipulators combine high stiffness to a low moving mass. This explains why these structures are used for high velocity applications. In the recent years several attempts have been made to apply dynamic balance to these type of manipulators \cite{12, 13}. Due to the high payload to robot mass ratio \cite{14} of parallel manipulators, the influence of added payload to the dynamic
balance is expected to be felt more strongly than with serial mechanisms. To the best knowledge of the authors, only one paper has been published with the explicit aim to provide adaptive dynamic balance for parallel mechanism. In this paper Lecours et al. [15] proposed movable masses to dynamically balance a five bar mechanism with a varying payload.

The simplest way to account for varying payload is by selecting the balance solution in between the unloaded and loaded case. However, this will result in some dis-balance. The aim of adaptive dynamic balance is to achieve less vibration than the “in-between” solution. Generally this means the throughput of the system has to be increased with adaptive dynamic balance. Therefore, the time of reconfigurations and the reconfiguration vibrations should be less than the in-between solution. Furthermore, the increased efficiency and accuracy of the mechanism should be worth the increased complexity and added actuators.

This paper aims to provide an overview of the complete set of strategies for force balancing taking varying payload into account, illustrate their basics using 1-DOF example and show their implementation in 3-DOF examples. Although parallel systems are expected to benefit the most from adaptive dynamic balance, the scope of this paper is limited to the force balance of serial mechanisms. As serial mechanisms cannot be moment balanced without additional structures, such as a reaction wheel [16], moment balance is currently not evaluated. First the dynamic balance equations are derived for the general serial case. From these dynamic balance equations the five strategies are established and illustrated for a serial 1-DOF case. The effectiveness of of these strategies are evaluated by implementation to a 3-DOF serial manipulator.

II. Dynamic balance equations

To understand the dynamic balancing conditions, first the mechanism definitions and mathematical notations are introduced. A reference frame is associated with each rigid body (denoted with a $\psi_i$). This reference frame can be placed anywhere as long as it is fixed with the body. We choose to attach these reference frames in the center of mass. The amount of mass associated to that center of mass (COM) is $m_i$. Each body is linked to the previous body by a joint, indicated with the subscript ($j_i$). The joint variables, e.g. joint angle or displacement, are indicated with a $q_i$. The location of the joints can be expressed with respect to a reference frame. These vectors are denoted with a superscript to indicate in which reference frame they are expressed. For example $j_{i+1}^k$ expresses the position of the second joint as seen by the first reference frame. The position of other reference frames expressed with the distance vector ($\psi_i^k$). The velocity between reference frames $i$ and $k$ with expressed the base frame is give by $v_{i,k}^k$. The changing payload ($m_o$) is assumed to be rigidly linked to the last link, the end-effector. This position vector is expressed with $r_{e}$.

The total center of mass of the mechanism is located at ($r_0$).

Dynamic balancing uses the momentum equations to find the conditions for which the total center of mass and inertia of the system is stationary. This means that when a mass moves with a certain velocity there is another mass which moves with the same momentum in the opposite direction. As we confine ourselves to force balance, only the sum of the linear momenta ($h_i$) of all subsystem must equate to zero.

$$h_i = \sum_{i=1}^{n} h_i = \begin{bmatrix} m_1 & \cdots & m_n \end{bmatrix} \begin{bmatrix} v_1 \\ \vdots \\ v_n \end{bmatrix} = Mv = 0$$

When it is assumed that the system does not have a continuous velocity and acceleration, the momentum equations can be equated to zero to attain dynamic balance.

The velocity vector for all bodies can be expressed as a function of the joint velocities using the Jacobian matrix ($J$).

$$Mv = MJ\dot{q} = 0$$

For the force balance of a serial linkage the total center of mass of each link and it sequential links should be located at its joint. The total aggregated mass of the i-th joint is $m_{j_i} = \sum_{k=i}^{n} m_k + m_i$. Starting from link $n$ down to base link 0 the balance conditions in the local reference frames are:

$$m_{j_i}^i = m_{i+1,i+1}$$

![Fig. 1. A force balanced serial mechanism. A reference frame ($\psi_i$) is attached the center of mass $m_i$ of each body. The origin of the reference frame $i$ with respect to each $k$ is expressed with $\psi_i^k$. The joints are indicated with $j_i$ and joint angle $q_i$. The variable payload ($r_{e}$) has a mass $m_o$.](image-url)
During a changing payload, not only the amount of mass at the end-effector changes, but also its associated inertia and application point of the mass. These changes are be neglected for sake of simplicity at the cost of completeness.

III. Strategies

Five strategies, discussed here, can achieve dynamic (force) balance for a varying payload. The first three strategies are derived from changing the three ingredients of Equation 4 (I) the position of the counter mass ($m_i^c$), (II) the position of the joints ($j_i^0$) and, (III) the value of the counter weight ($m_i$). The latter two strategies are derived from recognizing that the general balance conditions of Equation 2 can also be satisfied by adding additional DOF, which can counteract each other’s momentum. As long as the joint velocities ($\dot{q}$) are chosen such that trajectory is reactionless, not all elements of MJ have to equate to zero. These additional links can be placed on the base as a separate reaction mechanism (IV), or in the loop, resulting in the redundant joint strategy (V).

These strategies are illustrated with a simple 1-DOF force balanced mechanism, a seesaw (Figure 3). On both sides of the seesaw there two masses which are initially in balance. The mass on the right hand side is increased - the changed payload - leading to an imbalance of the mechanism. The five strategies are applied to restore the balance.

A. Strategy I. Reconfigure mass position

A stationary center of mass during varying payload can be achieved by the masses of all the links. This strategy is adopted by [4], [5]. For serial structures this boils down to moving the mass of each link such that the combined COM of the link and all posterior links is located at the link’s joint center. The distance between the mass and the joint should be enlarged with a factor proportional of the changed mass and the position of the next joint. The control law to achieve balance is found by differentiating the balance equations of (Equation 4). The positions of the joints with respect to the base ($j_i^0$, $j_{i+1}^0$) are constant, while the position of the mass is to be moved in order to keep the aggregated COM at the joints.

$$v_{i,i}^0 = \frac{m_i}{m_1} (j_i^0 - j_{i+1}^0)$$

A reconfiguration force is generated as the balancing masses are accelerated. This is proportional to the change of payload according to the following relation.

$$f = \sum_{i=1}^{n} m_i v_{i,i}^0 + m_1 g$$

Using the derivative of Equation 5 it can be seen that the change is reconfiguration force is proportional to distance between the joints and the second derivative of the payload.

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**Fig. 2.** The mass flow property of adaptive balance. The payload (yellow mass) is moved by the mechanism, shown as the red mass. The balancing mechanism, green mass, has to make a stronger counteracting motion when the mechanism is loaded. This will result in a “walk away” or “massing mechanism, green mass, has to make a stronger counteracting motion mass) is moved by the mechanism, shown as the red mass. The balance equation can be expressed in the base frame

$$m_i \dot{q}_i^0 + m_{i+1} \dot{j}_{i+1}^0 = m_i \dot{j}_i^0$$

Or similarly, the balance equation can be expressed in the base frame

$$m_i \dot{q}_i^0 + m_{i+1} \dot{j}_{i+1}^0 = m_i \dot{j}_i^0$$

$$(4)$$

It should be noted that for a planar serial mechanism it is sufficient for the aggregated mass of each link to placed on the axis passing through the linkage. From Equation 3 and Equation 4 the recursive nature of the balance conditions can be seen. This means that a change in the end-effector mass leads to a change in mass conditions for all the other links.

A. Preliminary remarks

As pick-and-place application by definition requires a continuous asymmetric motion of mass from one point to the other - the mass flow - another mass flow in the opposite direction is required [6]. The consequence of this mass flow is that the balancing mechanism does not return to its initial pose and “walks away”. This is illustrated with the use of a simple example for adaptive dynamic balance as shown in Figure 2. This mass flow can be circumvented by allowing a continuous mass flow in the opposite direction. Another option is to reconfigure the system during a motion phase that dynamic balance is not required. For reaction wheels the mass flow does not pose a problem as they are generally allowed to move indefinitely.

The boundaries of the system have to be determined precisely. If the conservation law of mass is to be held we should include the added payload as part of the system throughout the complete cycle. However, for simplicity reasons we will allow a change of mass at the payload. In the strict sense this is not correct. As a consequence, the total COM of the system changes without generating a reaction force. This is caused by the fact that the change in payload is actually a change in boundary of the system.

This change in payload also results in a change in size and application point of the gravitational vector. A complete constant reaction wrench is therefore only possible by continuous opposite acceleration of a counterweight. In the rest of the document this is not taken into account and the change in gravitational vector is taken for granted.
ψ

\( m_a \)

\( v \)

\( r_b \)

\( r_a \)

\( \sum_{i=1}^{n} \)

\( j_{i+1} \)

\( j_{i} \)

\( m_i \)

\( g \)

\( f = \dot{m}_v \sum_{i=1}^{n} (j_{i} - j_{i+1}) + m_t g \)

\( \dot{j}_i = \frac{\dot{m}_a}{m_i} j_{i+1} + \frac{m_{i+1}}{m_i} j_{i+1} \)

The first term is mainly responsible for the change in reaction force. The last term only has the change in magnitude of the gravity term as consequence of the change in payload which was said to be neglected.

**B. Strategy II. Reconfigure joint position**

A serial mechanism is force balanced when all the revolute joints axis intersect with the aggregated COM associated to that link. When this aggregated COM moves due to a changed payload, dynamic balance can be restored by moving the joint axis to intersect again with this COM. Something similar has been proposed in [6]. For a 1-DOF planar system at least two prismatic joints are required; one at each side of the revolute joint. When the COM is changed the revolute joint can be placed to intersect the with COM. When the reconfiguration has taken place the joints can be locked, reducing the energy consumption. It should be clear that the current implementation of this strategy to the 1-DOF mechanism, can only account for a change in load if both prismatic joints are parallel. This happens when the joint angle is 0 or 180 degrees. To allow reconfigurations in other poses, additional prismatic joints have to be used.

For this strategy, the control law is derived from Equation 3.

\[ \dot{j}_i = \frac{\dot{m}_a}{m_i} j_{i+1} + \frac{m_{i+1}}{m_i} j_{i+1} \]

It should be noted that the position of the joint is influenced both the change of the payload, and the change in position of the sequential joints.

The range of motion and the kinematics are altered due to the changed distances between the joints. This increases the complexity of the system. The advantage of this strategy is that no reaction forces are required to achieve the reconfiguration, as the prismatic joints are assumed to be massless. In reality the joints contain some mass and friction and a reconfiguration force will be exerted.

**C. Strategy III. Change the counterweight value**

The third strategy relies on changing the amount of counterweight to counteract the change in payload. In practice, the addition of mass can be achieved by moving a mass from the base to the counterweights of the links. This can be achieved for example, by pumping a fluid through the system. This will generally require reconfiguration force as the mass is moved through the mechanism. In [6] two implementations, using liquid and magnetic particles, are discussed.

For the control law the derivative of the balance equations in the local frame Equation 3 suffices.
\[ \dot{m}_j = (\dot{m}_v + \sum \dot{m}_i) ||\dot{j}_{i+1}|| \quad (10) \]

When the relation between the joint distances \( g = \frac{||j_{i+1}||}{||j_i||} \) is equal over all the links, the control law simplifies to an exponential relation:

\[ \dot{m}_i = \dot{m}_v g (g + 1)^{n-i} \quad (11) \]

Generally the addition of mass will generate forces proportional to the acceleration of the added mass. However if the mass is added simultaneously from opposite directions, these forces cancel out each other.

It should be noted that if the COM of payload changes, this method will not generate sufficient results. Only in the special case as the payload is shifted along the center line passing through the counterweight and the pivot, rebalance can be obtained.

### D. Strategy IV. Reaction mechanism

Inspection of Equation 2 gives rise to two other strategies for adaptive dynamic balance. Additional links, placed at the base can be used to counteract the motion of the initial mechanism. The additional links, the reaction mechanism, must be steered in such a way that dynamic force or moment balance is achieved. In [7] this method is used for a XY table. The control law can be derived by decomposing Equation 2 for both the initial \( a \) and the reaction mechanisms \( b \).

\[
\begin{bmatrix}
M_a & M_b \\
J_a & 0 \\
0 & J_b
\end{bmatrix}
\begin{bmatrix}
\dot{q}_a \\
\dot{q}_b
\end{bmatrix}
= 0
\]

The joint velocities of the reaction mechanism can be found uniquely if the inverse exist of the \( M_a J_b \) matrix.

\[ \dot{q}_b = -(M_a J_b)^{-1} M_a \dot{q}_a \quad (13) \]

This inverse exists as long as reaction mechanism is not in a singular configuration. For the 1-DOF example, this is the case when both reaction masses are aligned. Another singularity exists when the reaction mechanism in itself is balanced. When the initial mechanism (part \( a \)) is balanced, loaded or unloaded, the reaction mechanism does not need to act.

In this strategy, the reaction mechanism can only be used for balancing the mechanism. Only in the special case when reaction mechanism consists of a mirror of the initial mechanism, the system can be used for opposite pick-and-place action. The range of motion is depending on the change in payload.

### E. Strategy V. Redundant joints

The fifth strategy uses additional DOF within the kinematic chain to obtain adaptive balance. This method is firstly proposed by Yoshida et al. [10] for operation in space. Similarly to the previous strategy, these additional DOF can be controlled in such a way that the total momentum equates to zero. When the number of joints is larger than the required DOF of the end-effector, the kinematic relation between the end-effector pose \( \{x\} \) and the joint coordinates \( \{q\} \) is under defined.

\[ \dot{x} = C \dot{q} \quad (14) \]

This freedom to move the joints without affecting the pose of the end-effector is called the null space. The control of the null space can be used to satisfy the balance conditions.

From the null-space, a trajectory can be selected for which the total momentum is zero. This requires at least one additional joint per balanced direction to achieve the same DOF at the end-effector. In the current 1-DOF seesaw example, force balance in two directions requires two additional redundant joints resulting in a RRR-mechanism. The constraints of Equation 2 and Equation 14 are combined to give a matrix relation between the end-effector velocity and the joint coordinates.

\[
\begin{bmatrix}
MJ \\
C
\end{bmatrix}
\dot{q} =
\begin{bmatrix}
0 \\
\dot{x}
\end{bmatrix}
\]

If this system of equations is properly dimensioned, meaning the left matrix is square, and an inverse of this matrix exist, the control law for the joint velocities as a function of the required end-effector velocity can be found.

\[
\dot{q} = \left[ MJ \begin{bmatrix} I \\ C \end{bmatrix} \right]^{-1} \begin{bmatrix} 0 \\ I \end{bmatrix} \dot{x}
\]

Again singularities occur, limiting the range of motion of the end-effector. These singularities exist when three consequential joints of the mechanism are aligned. In case of a RRR-mechanism, a singularity occurs when one of the joints has an angle of 0 or 180 degrees. These singularities are similar to the ones existing in a five bar mechanism. There are more similarities between the five bar mechanism and the current 1-DOF example. The system will be controlled as if it was a force balanced five bar mechanism. A four virtual joint will be rendered somewhere on the mechanism. If the additional links have no mass, the virtual joint coincides with the COM of the mechanism, as shown in [11]. This will result in a circular trajectory of the end-effector. When the mass of the mechanism is changed, the virtual joint can be displaced without effort. If the additional coupler links have a mass which is not dynamically
balanced, still a 1-DOF trajectory is attainable. However, this trajectory will be an ellipse and not a circle.

This strategy has the advantages that it can render dynamic balance for an otherwise not balanced mechanism. It does not require addition of counterweights. The downside of the mechanism is mainly its limited workspace. One part of the mechanism has to counteract the motion of the other links, this counteraction quickly results in singularities of the mechanism. As the unloaded mechanism must balance the payload, it cannot be balanced in itself. If the loaded system is balanced the system gains an additional freedom during the loaded phase.

The range of motion of the mechanism can be increased by relaxing the dynamic balance on moments that accuracy is less required, for example in between the pick-and-place action. When the dynamic balance requirement is relaxed, the null-space can also be used for other means, such as avoiding obstacles or reducing the energy consumption.

IV. Examples

In this paper, five strategies have been exemplified using a simple 1-DOF open loop mechanism. To see the consequence for more complex architectures the strategies are shown for a 3-DOF planar mechanism. In Figure 4 the five mechanisms are depicted. Again, only force balance is considered, since serial mechanisms cannot be moment balanced without addition structures. Also the attachment point of the payload is kept stationary.

A quantitative comparison between mechanisms is difficult as the dimensions and weights are not comparable over the structures. However, to gain some insight into the value of, for example, the reaction and reconfiguration forces, numbers are assigned to the mass and the mass change. The payload changes from initially 1 kg to a final 2 kg. The change in payload \( \Delta m \) follows a trapezoid function, in which the ramp up and ramp down takes 0.1 seconds. The coast time is 0.1 s. From the trapezoid trajectory equations follows that the maximal mass change is 5 kg/s and the second derivative of the payload is 50 kg/s². For the reconfiguration strategies (I-III) the link length is 1 m and the initial position of the joint is at 1/3 of the link. The balance equations \([\text{Equation} 3]\) leads to initial counterweights of the first to the last link of 18, 6, and 2 kg respectively. For the control strategies (IV - V) the total length (3 m) and the total mass (26 kg) are equal to the reconfiguration strategies. All the links are assumed to have equal lengths and equal mass.

A. Strategy I. Reconfigure mass positions

For 3-DOF serial linkage with force balance three prismatic joints are required to move the mass the counterweights to a balanced position. The amount of displacement can be calculated by applying \([\text{Equation} 3]\) for the final payload. Also \([\text{Equation} 8]\) can be integrated over time. The counterweight displacements are 1/27, 1/9, 1/3 m, respectively.

The reconfiguration force is only depending on distance between the joints and the second derivative of the payload mass \([\text{Equation} 7]\). This is maximal when the directions of acceleration are parallel, which happens at the outstretched position. The maximal change in reaction force is approximately 100 N.

B. Strategy II. Reconfigure joint positions

The configuration of the joints requires 12 additional joints; four joints per actuator. The displacement of the joints can be calculated from \([\text{Equation} 3]\). For simplicity reasons the displacement is only calculated for the outstretched case. Then the joints are all moved in the same direction. In any other configuration the rotation of the joints with respect to each other has to be taken into account, complicating the calculations. For the last link, its joint has to move to the middle of the link, as the masses on both sides are now equal, a distance of 1/6 m. For the second link the attachment point of its associated mass moves also with a 1/6 m. The joint motion has to account this change plus the change in added load, resulting in a displacement of 2/15 m. For the base link, a displacement of 1/14 m will be required. It can be seen that the displacement near the end-effector is larger than near the base. This can also be seen from expanding \([\text{Equation} 8]\).

\[
\mathbf{j}_1 = \frac{\dot{m}_w}{m_3} r_3^2 
\]

\[
\mathbf{j}_2 = \dot{m}_v \left( \frac{1}{m_2} + \frac{m_w + m_3}{m_2 m_3} \right) u_3^2
\]

As the part in between brackets is always smaller than 1/m₃, the change in displacement becomes smaller near the base. The total range of motion of system reduces from a circle with a radius of 2 m, to circle with a radius of 1.63 m.

C. Strategy III. Change mass

For current embodiment a liquid is pumped to the counterweights to counter balance the change in payload. However, the change in payload location cannot be accounted for. It should be noted that the change in mass is 5 kg/s and the second derivative of the mass change is 50 kg/s². For the reconfiguration strategies (I-III) the link length is 1 m and the initial position of the joint is at 1/3 of the link. The balance equations \([\text{Equation} 3]\) leads to initial counterweights of the first to the last link of 18, 6, and 2 kg respectively. For the control strategies (IV - V) the total length (3 m) and the total mass (26 kg) are equal to the reconfiguration strategies. All the links are assumed to have equal lengths and equal mass.

The final mass of the linkages will be calculated from \([\text{Equation} 11]\) to be 36, 12, 4 kg. The total addition of mass is \(m_b = 26\) kg. This mass has to flow from the tank to the counterweights. This flow will generate a reaction force due to the acceleration and deceleration of the liquid.

The final mass of the linkages will be calculated from \([\text{Equation} 11]\) to be 36, 12, 4 kg. The total addition of mass is \(m_b = 26\) kg. This mass has to flow from the tank to the counterweights. Similar to \([\text{Equation} 7]\) the reaction force is not depending on the amount of mass that is moving, only...
Fig. 4. The five strategies applied to planar 3 DOF mechanisms. (a) The reconfigure mass position strategy (I) requires one additional prismatic joint (lockable) per counterweight. One additional slider to the last link is added to allow correction to the payload attachment point offset. (b) The reconfigure joint position strategy (II) uses four additional revolute (lockable) joint per actuator joint, two on each side of the actuator joint. (c) The amount of mass (III) can be changed by pumping liquid from the reservoir to the counterweight. The liquid is depicted in blue. The counterweights are expanded in opposite directions. A reaction mechanism (IV) is added in (d) to be controlled in order to keep the total center of mass stationary after changing the payload. In (e) two additional joints (IV) are placed in the serial chain. This results in a null-space with a dimension two. The null-space is controlled to satisfy the two force balancing constraints.

the distance of the payload matters. Similar to the reconfigure mass position the reaction forces are 100 N. The reconfiguration moment however changes. These equations assume that the liquid tank and the mechanism have the same base. If the same equations are done for different bases the reconfiguration forces are much higher. Also gravity vector changes much more.

D. Strategy IV. Reaction mechanism

A 2-DOF reaction mechanisms is added to the 3-DOF serial linkage to generate force balance. The counteracting motion is calculated from Equation 12. For comparison with the other mechanisms, the lengths of all the links are equal to 2/3 m and contain a mass of 5.2 kg. The choice of these masses and sizes strongly influence the range of motion of the mechanism. Singularities occur when Equation 12 loses rank. The range of motion can be enlarged by relaxing the force balance equations during the in-flight phase of the trajectory.

E. Strategy V. Redundant joints

Similar to the 1-DOF case, two additional joints are required to account for the force balance conditions while allowing planar motion of the end-effector. No further reconfiguration forces occur. The range of motion of the system is now limited by the singularities of the mechanism. The addition of mass and the choice of counterweights have a strong influence on the range of motion. In this strategy the range of motion is limited by singularities of matrix Equation 16. The range of motion of this system can be increased if the dynamic balance is not required throughout the range of motion.
Additional joints can be used to satisfy other motion criteria. The redundant joint strategy (V) has an advantage over the other strategies. Granted that dynamic balance is not required throughout the complete motion cycle, the active strategy has an advantage. Also these active strategies require additional active moment balancing. The other strategies cannot achieve this in a serial structure. The active strategies (IV and V) can be used to obtain adaptive dynamic balance. The moving joint strategy (II) requires four additional (lockable) joints per active joints for the planar case, and even 6 for the spatial case. The variable counterweight strategy also does not seem viable as it requires large addition of counterweight for a small change in payload. The added mass increases to the power of the DOF times. The added mass increases to the power of the DOF.

The mass flow effect is observed in all strategies. It depends on the strategy how this is observed. During reconfiguration of the joint, the joint walks away. During variable counterweight strategy the mass (e.g. water) has to be dumped during the unloading phase to avoid a reconfiguration force. For redundant joint strategy the links do walk away, for reaction mechanism, the mechanism walks away. This mass flow can only be canceled by continuous, constant correcting velocity in opposite direction. By allowing an off-balance during part of the trajectory this mass flow can be compensated.

Dynamic balance of serial mechanism has limited potential as it requires large amounts of added mass to balance the mechanism. Future research has to show the effects of these strategies on the adaptive dynamic balance of parallel manipulators. It is expected that the same strategies can be used on parallel mechanism with higher gains as the mechanism-mass-to-payload ratio is much more favorable compared to serial structures.

### V. Discussion

Throughout the article, several advantages and drawbacks of the adaptive dynamic balance strategies are reported. An overview of these (dis)advantages for the five strategies can be found in Table I. With strategies I and III a reaction force can be expected during reconfiguration. This force is generated in the motion phase when complete balance usually is required, the pick or place phase. The reconfiguration strategies (I & III) require some time to adapt to the change in payload. Especially the variable counterweight strategy (III) suffers from this, as the variable mass (e.g. the liquid) has limited velocity and acceleration. The workspace of strategies (II, IV, and V) change with a adjusted payload. This can be circumvented by relaxing the force balance requirement during the mid-phase of the trajectory. All strategies require additional structure (joints, linkages etc.) to allow adaptive dynamic balance. The moving joint strategy (II) requires four additional (lockable) joints per active joints for the planar case, and even 6 for the spatial case. The variable counterweight (III) strategy also does not seem viable as it requires large addition of counterweight for a small change in payload, in our case 26 times. The added mass increases to the power of the DOF of the system. The variable counterweight strategy cannot balance a change in attachment point of the payload. The active strategies (IV and V) can be used to obtain adaptive moment balancing. The other strategies cannot achieve this in a serial structure. The active strategies (IV and V) have the disadvantage that a continuous motor forces are required to maintain static positions, they are not statically balanced. Also these active strategies require additional active joints. The redundant joint strategy (V) has an advantage over the other strategies. Granted that dynamic balance is not required throughout the complete motion cycle, the additional joints can be used to satisfy other motion criteria such as larger range of motion, low energy trajectories or obstacle avoidance. During the moments that dynamic balance of importance, the balance constraints can be satisfied using null-space control. This does not apply to the actuators of other strategies as they cannot serve another purpose than dynamic balance.

In the current paper, the strategies are separated. For the more advantageous effect the different methods can be combined. A reaction mechanism can be added to passive structures to obtain moment balance. To reduce the energy consumption of the control strategies, a lockable balance joint can be included into the mechanism. Depending on the application and required energy consumption a combination of strategies IV. and V. seem favorable. The reaction mechanism can be responsible for the moment balance while the additional links can be used other uses such as force balance. This way, the range of motion can be significantly larger without compromising the simplicity.

The mass flow effect is observed in all strategies. It depends on the strategy how this is observed. During reconfiguration of the mass position, the mass walks away, during configuration of the joint, the joint walks away. During variable counterweight strategy the mass (e.g. water) has to be dumped during the unloading phase to avoid a reconfiguration force. For redundant joint strategy the links do walk away, for reaction mechanism, the mechanism walks away. This mass flow can only be canceled by continuous, constant correcting velocity in opposite direction. By allowing an off-balance during part of the trajectory this mass flow can be compensated.

Dynamic balance of serial mechanism has limited potential as it requires large amounts of added mass to balance the mechanism. Future research has to show the effects of these strategies on the adaptive dynamic balance of parallel manipulators. It is expected that the same strategies can be used on parallel mechanism with higher gains as the mechanism-mass-to-payload ratio is much more favorable compared to serial structures.

### VI. Conclusion

Adaptive dynamic balance aims to achieve constant reaction forces under a varying payload. Five strategies for adaptive dynamic balance are compared here. The first three strategies depend on reconfiguration of the mechanism, the latter two use addition degrees of freedom to generate a trajectory which is reactionless. The first strategy moves the counter mass of the links to achieve stationary COM. The second strategy moves the joints to satisfy the balance equations. The third strategy, changes the mass of the counterweight. In the last two strategies additional DOF are added to the linkages. These additional DOFs allow the mechanism to be controlled over a reactionless trajectory.

These five strategies are exemplified and compared using 1-DOF and planar 3-DOF examples. From these examples it can be seen that not all strategies are equally use-
ful for adaptive balancing of complex serial structures. For example, the reconfiguration of the joints strategy requires at least 4 additional lockable joints per active joint for the planar case and 6 additional joints for the spatial case. It is not expected that the adaptive balance conditions justify this added complexity. It is also observed that a reconfiguration force occur for the mass reconfiguration and variable counterweight strategies. These forces arise at the moment which is usually most crucial, the pick or place phases. The first three strategies suffer from the drawbacks associated with dynamic balance of serial manipulators; large counterweights and complexity. The latter two, the control strategies, can achieve similar dynamic balance at the cost of added actuators, energy consumption and singularities.

References


