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► **To cite this version:**

Yash Vyas, Marco Tognon, Silvio Cocuzza. Force-balanced 2 Degree of Freedom Robot Manipulator based on Four Bar Linkages. 2024. hal-04428061v2

**HAL Id: hal-04428061**

**<https://hal.science/hal-04428061v2>**

Preprint submitted on 8 Mar 2024

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# Force-balanced 2 Degree of Freedom Robot Manipulator based on Four Bar Linkages

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**Abstract.** We design a force-balanced 2 degree of freedom planar manipulator, which has minimized ground reaction forces, reaction torques and joint actuation torques. This manipulator is highly suitable for mobile robotics applications, in particular for aerial manipulation, as it enables greater precision and stability. The design synthesizes two four bar linkage mechanisms together in a planar configuration. Each mechanism is optimally force-balanced through an algorithm that extends the links, aggregates additional components, and applies counter-masses. We compare dynamic simulation results for a trajectory between the unbalanced and balanced designs to validate that the latter has 59% reduction in reaction torques and a constant reaction force vector caused by gravity on the base, as well as lower joint actuation torques.

**Keywords:** dynamic balancing, four bar linkage, robot manipulation

## 1 Introduction

Mobile robot manipulation offers several advantages in completing industrial tasks, such as safety, cost, and efficiency. However, manipulators designed for these applications are designed as serial or spatial closed-chain manipulators [3]. This results in significant reaction torques and forces caused by motion of the manipulator center of mass (CoM) and joint torques during manipulation.

Proposed solutions to this include differential inverse kinematic approaches [4, 6], or mechanical design to balance the CoM [1]. In this research, we explore the idea of force balancing [7] to design a force-balanced manipulator suitable for mobile (particularly aerial) manipulation applications [3]. The CoM of the mechanism is static, resulting in a constant reaction force on the mechanism. Some existing investigation in this field includes balancing delta arms or pantographs [2, 5].

In this research paper, we utilize kinematic equations for force-balancing [8] and synthesis [9] of closed-chain four-bar linkage (4BL) mechanisms, to design a 2 degree of freedom (DOF) planar manipulator. We apply the force balance equations of a four-bar linkage to an optimization methodology which calculates the counter-masses that balance the manipulator while minimizing the total mass. The dynamic behavior of unbalanced and balanced designs is verified in simulation and compared.

## 2 Background

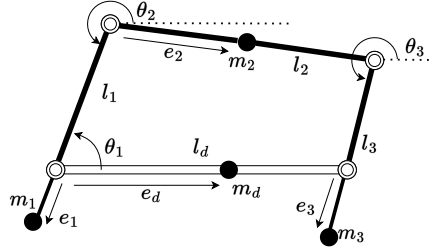


Fig. 1: A force-balanced four bar linkage diagram.

We use the generalized coordinates and kinematic parameters as shown in in Fig. 1, assuming that the CoM is inline for each link. For link  $i$  with revolute joint causing motion about generalized coordinate  $\theta_i$ ,  $l_i$  is the length,  $e_i$  is the in-line vector to the center of mass  $m_i$ , with  $d$  being the fixed bar. The conditions required for force-balance of a 4BL mechanism are derived in [8]:

$$m_1 e_1 + m_2 \left(1 - \frac{e_1}{l_2}\right) l_1 = 0 \quad m_3 (l_3 - e_3) + m_2 \frac{e_2}{l_2} l_3 = 0 \quad (1)$$

For any set of values of  $\theta_1, \theta_2, \theta_3$  that fulfill the closed loop constraints, the center of mass of the balanced 4BL is fixed and can be found in terms of coordinates  $e_i$  with respect to the axis of fixed bar  $l_d$ . It is important to note that the kinematic parameters defined here are aggregate for the entire link, and include counter-masses.

## 3 Method

We utilize the force balanced equations of a 4BL to design a 2-DOF manipulator, made by synthesizing two force-balanced 4BLs as outlined in [9] for a dynamically balanced four bar linkage. An illustrative figure of the mechanism is shown in Fig. 2. Kinematic parameters and coordinates use dual indexes  $ji$ , where  $j$  is the 4BL and  $i$  is the link or joint index. 4BL1 with  $j = 1$  is attached to 4BL2 with  $j = 2$ , which is mounted on the base.

To conserve space, simplify the mechanism design, and reduce interference, we opt for a crossed over kinematic configuration for link 2 with the counter-masses attached to links with  $i = \{1, 3\}$ . Constant parameters are the link lengths, as well as positions and loads of additional mechanical components (e.g. joints, motors, and payload at the end effector). These are aggregated into a single link mass  $m_i$  with center of mass at  $e_i$ . Each 4BL is then optimized through extending the link geometry and attaching counter-masses through a constrained optimization function, where the objective function is minimization of the total mass  $\min \sum_{i=1}^3 m_i$ , variables are the counter-masses, subject to (1).

The optimization is done recursively, e.g. 4BL1 is optimized first, and then modeled as a single mass load applied on  $L_{23}$ , which is then also optimized. The combined manipulator is 2-DOF as  $\theta_{11}$  moves the end effector through

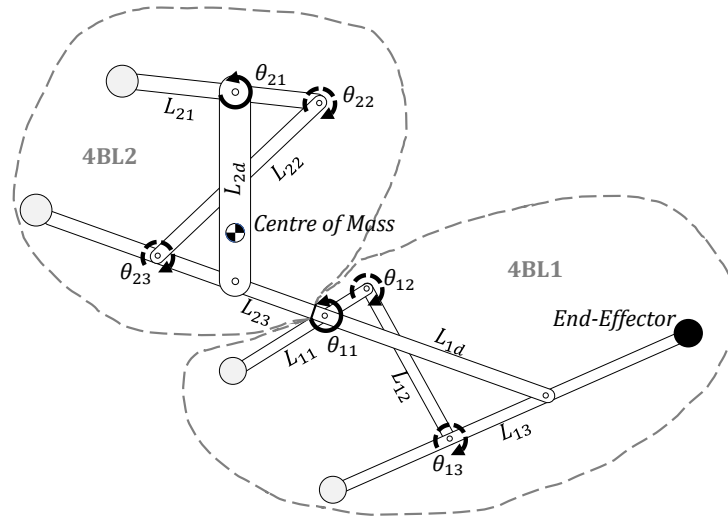


Fig. 2: The 2DOF manipulator built from mounting 4BL1 on 4BL2. Joints are indicated by their coordinate  $\theta_{ji}$  and links are  $L_{ji}$ . Actuated Joints (solid arrow), passive joints (dashed arrow), and counter-masses (shaded circle) are indicated.

constrained motion of  $\theta_{13}$ , and 4BL1 moves in relation to  $\theta_{23}$  which moves constrained as actuated by  $\theta_{21}$ .

## 4 Results

We applied the method outlined to design a 2-DOF force balanced manipulator that is comparable to a serial link manipulator with maximum extension of 0.5m. 4BL1 is mounted with extension  $e_{23} = 0.35\text{m}$  on 4BL2 and the end-effector is mounted at an extension of  $e = 0.35\text{m}$  on 4BL1, to achieve this maximum extension. We set the length proportions  $l_{j1} = l_{j3}$  and  $l_{j2} = l_{jd}$ , so that singularities occur when  $L_{j1}$ ,  $L_{jd}$ , and  $L_{j3}$  align simultaneously. The ratio of link lengths selected for  $L_{j1} : L_{j2}$  results in a roughly elliptical and convex workspace with an area of  $0.386\text{m}^2$ .

We model the mechanism with revolute joints (consisting of bearings), link mass, motors (attached to the fixed bars) and an end-effector payload of 300g, similar to an equivalent 2-DOF serial link manipulator used to move a load. The original, unbalanced mechanism with these loads is then balanced by extending the links to include counter-masses.

Table 1 shows the geometric and kinematic parameters for each link with additional loads (joints and payload) aggregated with the link profile, for both the unbalanced and balanced manipulator mechanisms. The mass of the unbalanced mechanism is 1.464kg and the balanced mechanism is 2.330kg (44% heavier).

The design was implemented in MATLAB, through modeling of the links and optimization of counter-masses using the `fmincon` function, and finding the corresponding joint velocities for an end-effector trajectory using inverse kinematics as a constrained least squares minimization problem. The end-effector

Link	$l$ (m)	Unbalanced			Balanced				
		$m$ (kg)	$e$ (m)	$I(10^{-3}\text{kg}\cdot\text{m}^2)$	$m_{cm}$ (kg)	$e_{cm}$ (m)	$m$ (kg)	$e$ (m)	$I(10^{-3}\text{kg}\cdot\text{m}^2)$
$L_{21}$	0.16	0.0728	0.0386	3.076	0.06124	-0.1579	0.1687	0.0569	2.490
$L_{22}$	0.2	0.0816	0.0538	0.5933	–	–	0.0822	0.0541	0.5906
$L_{23}$	0.16	0.1057	0.0997	0.9266	0.7576	-0.1579	0.8984	-0.126	21.32
$L_{2d}$	0.2	0.1636	0.0729	3.891	–	–	0.1636	0.0729	3.891
$L_{11}$	0.12	0.0640	0.0247	0.1342	0.05417	-0.12	0.1445	-0.0450	1.199
$L_{12}$	0.15	0.0706	0.0350	0.2548	–	–	0.0706	0.0350	0.2548
$L_{13}$	0.12	0.1079	0.1041	0.7137	0.2149	-0.12	0.3492	-0.0462	4.408
$L_{1d}$	0.15	0.1526	0.0532	2.117	–	–	0.1526	0.0532	2.117

Table 1: Parameters for the design of the synthesized 4BL, for the links shown in Fig. 2. Parameters are as denoted in Figs. 1 and 2, and  $m_{cm}$  indicates the counter-mass separately.  $I$  is the moment of inertia of each link about joint  $\theta_{ij}$ .

was moved smoothly to the waypoint  $[x, z]^T = [0.15, 0.1]^T$  relative to its original position in 1s, holds for 0.5s, and moves back to the starting position in 1s. The unbalanced and balanced models were implemented in ADAMS to obtain accurate estimates of reaction torques/forces on the base (as measured at the mount point), and the joint torques. The results are shown in Fig. 3.

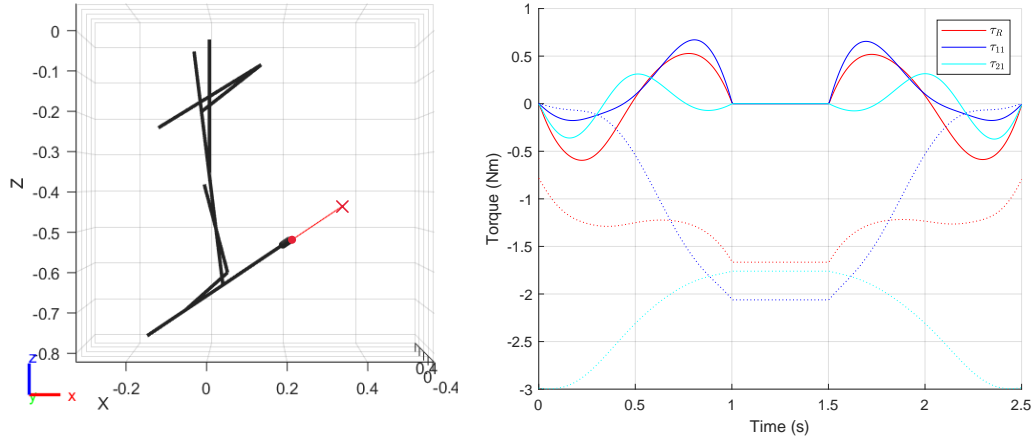


Fig. 3: Trajectory tracked at left: indicating start/end position (dot) and tracked waypoint (cross). Torques at right:  $\tau_R$  is the reaction torque, actuated joint torques are  $\tau_{11}$  and  $\tau_{21}$  for balanced (solid) and unbalanced (dotted).

We observe force balancing in the optimized mechanism through a constant linear reaction force for the optimized manipulator, whereas the unbalanced fluctuates to a maximum of 0.775N. Furthermore we can observe a much lower maximum absolute reaction torque of 0.595N.m for the balanced mechanism as compared to 1.66N.m for the unbalanced mechanism. The joint torques are also reduced by 67-92% due to reduction of gravity torques.

## 5 Conclusions

A 2-DOF force-balanced manipulator composed by synthesizing two 4BLs offers several benefits, the most important being a reduction in reaction torques and fluctuations in the reaction force. By aligning the CoM of the manipulator to the base mounting point, we also eliminate any reaction torques caused by gravity forces. Although the inertia of the mechanism increases due to the addition of counter-masses and extension of links, we find that the increase in motor and reaction torques from this is less with respect to gravity-induced torques in the unbalanced case.

Force balancing also helps to reduce the disturbance forces and vibrations between the base and manipulator. This makes this manipulator suitable for mobile platforms as it facilitates more precise execution of manipulation tasks. As the reaction forces are constant and the reaction torques are reduced, it also enables a much simpler control mechanism for the mobile base. In future research to further explore this concept, we will investigate different tasks such as load picking/interaction with the environment, and the dynamic interaction between the base and manipulator.

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The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement no 101034319 and from the European Union — NextGenerationEU.