Designing Cable-Driven Parallel Robots for Pick-and-Place Operation with Low Energy Consumption and Minimal Use of Resources

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Abstract Industrial pick-and-place robots constitute nearly half of the world's operational robotic systems and represent a major share of industrial robots' energy consumption. Reducing their energy demand is therefore essential for both economic and environmental reasons. In this paper, we focus on operation at low or moderate speeds, possibly involving large load and/or large workspace. We present a concept and prototypes of a cable-driven parallel robot (CDPR) controlled by an electromechanical system. This system remains programmable but does not require a computer, drastically reducing both energy consumption and the use of electronic boards.

1 Introduction

The number of industrial robots in operation continues to grow in manufacturing and industrial environments due to their ability to deliver fast, flexible, and reliable production, characterized by high accuracy and repeatability [12]. In 2022, more than half a million new robots were installed worldwide [9].

Nearly half of them perform handling operations, such as *pick and place (PP)*, which are simple and highly repetitive tasks. A typical PP trajectory consists of picking a part at pose A, moving it vertically, and then along a trajectory toward the vertical above a position B, before finally depositing the part at B. Therefore, the task requires the robot to have only 2 or 3

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d.o.f. (with possibly an additional rotation d.o.f. to change the orientation of the part between A and B) [5]. Consequently, most PP-robots have either a Cartesian, SCARA, or serial mechanical architecture or, when very high speed and light load are required, are of the Delta parallel type. The first drawback of classical PP robots is that their load-to-robot-weight ratio, μ, is low, meaning that the moving mass of the robot, in addition to the load, is large. As a result, these robots generally exhibit poor energy efficiency, with the notable exception of the Delta robot. A second drawback is that they all have a limited workspace, with μ decreasing as the workspace size increases. Finally, the loads they can manipulate are usually very limited. Several studies have addressed energy consumption reduction either through trajectory planning [10] or robot placement optimization [11]. However, these approaches lead to a non-neglegible but limited reduction of energy consumption.

The growth of handling operations automatically leads to a significant increase in energy consumption in factories, which is a concern in the context of global environmental objectives and the reduction of greenhouse gas emissions. Furthermore, current pick-and-place robots rely on computers and electronic boards that account for a large share of their energy consumption (between 20 and 40% of the total energy consumption [6]) and use resources whose extraction and exploitation also have a negative environmental impact.

In this paper, we focus on pick-and-place at low or moderate speeds, allowing for large workspaces and/or heavy loads. We propose a solution that drastically reduces energy consumption, minimizes the use of electronic resources, and allows for easy maintenance.

2 Choice of mechanical architecture

A first lever for energy reduction is the choice of the robot architecture. Robots with parallel architectures are more energy-efficient than those with serial architectures (with a decrease in energy consumption of about 25%) [8]. Consequently, they have been used in various applications that require low energy consumption, such as solar tracking [1] or 3D printing [4].

Cable-driven parallel robots (CDPR) present additional advantages: they are lightweight and modular (their geometry can easily be modified to adapt the robot to a given task), and they can cover large workspaces while carrying heavy loads. Unlike conventional rigid architectures, they rely on the winding and unwinding of lightweight cables on fixed winches to move a mobile platform, which significantly reduces the moving mass [7]. Here again, several studies have investigated trajectory planning to reduce energy consumption [2],[3]. However, as mentioned in the introduction, a significant portion of the energy consumed by a robot comes from its control computer—which is often oversized for simple tasks such as pick-and-place operations—and from the electronic boards required for robot control. This constitutes the second lever we exploit to reduce both energy consumption and resource usage.

3 A new control concept

3.1 General principle

We will first focus on a PP robot with 2 d.o.f. namely translations along the **x** and **z** axes. For a cable-driven parallel robot, these motions can be achieved using 2 cables connected to the same point B on the platform, referred to as a *2-1* CDPR (Fig. 1). In our case, the cables are wound on *cable drums* equipped with a spiral guide that translates to keep the cable exit point at a fixed position. We assume that the pick and place positions are perfectly known, and we consider a symmetric trajectory (Fig.1). From the pick position P_1, the robot performs an upward motion to P_2. It then transfers the object to P_3 along a non-strictly defined trajectory and finally performs a downward motion toward the place position P_4. As a first example, we choose a trajectory involving 80 cm horizontal motion and 18 cm vertical motion.

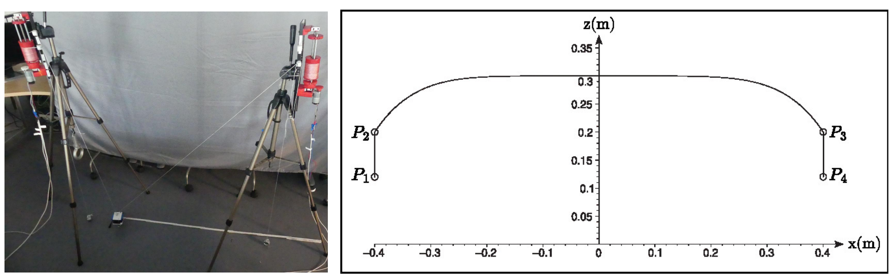

Fig. 1 A 2-1 CDPR and our first example of pick-and-place trajectory

Once both the trajectory and the velocity profile are fully defined, kinematics can be used to compute the cable winding speeds (and consequently the cable drums' rotational speed) of the CDPR as functions of time. The originality of our approach lies in the fact that we do not use a computer to control the cable drums' velocities. Instead, we employ a simple motor control board that takes as input two voltages between 0 and 5V and regulates the velocities of the motors accordingly. These voltage signals are generated using an electromechanical approach based on a 3D-printed cylindrical *command drum cam* which is driven at a constant angular velocity by a small, very low-power motor (Fig. 2). The drum features a groove that serves as a guide for two sliders, which translate parallel to the rotation axis of the command drum cam and actuate potentiometers (one per motor). The resulting voltages are used as input signals for the motor control board. The groove is designed such that it reflects the cable velocities required to perform a complete cycle (the load starting from P_1, moving to P_2, P_3, P_4 and returning to P_1). As a result, continuous rotation of the control drum cam enables the execution of an arbitrary number of complete cycles. Grasping and release of the load is ensured by an on-board electromagnet that is activated by a radio-controlled switch.

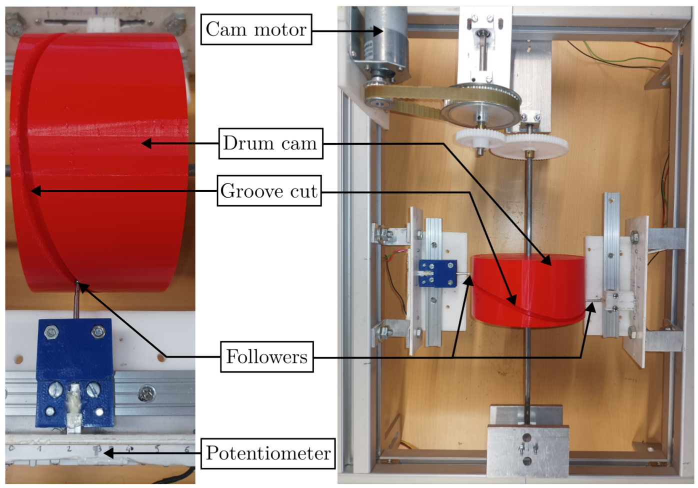

Fig. 2 The electromechanical command system

3.2 Drawbacks and solution

A drawback of this approach is that the groove cannot reflect all possible cable velocity profiles, as it has to present a smooth slope; otherwise, the sliders may become stuck. This limitation, combined with clearance in the sliders, leads to a drift in the robot pose that increases with the number of cycles. To address this issue, we use 4 micro-switches I_j^k located near the cable drum of cable k where I_j^k is actuated when the length of the k-th cable corresponds to the pose P_j. We then use a system of relays to switch from differents control modes of the motors: V^+ and V^- are fixed voltages that are used to perform approximate vertical motions, MC is the control mode with the command drum cam voltage signals for the transfert motion, and 0 is to turn off the motor. An exemple of state machine diagram is given in

Fig. 3 for the forward trajectory. This method ensures that the platform is correctly positioned in P_1 for the picking and in P_4 for the placing.

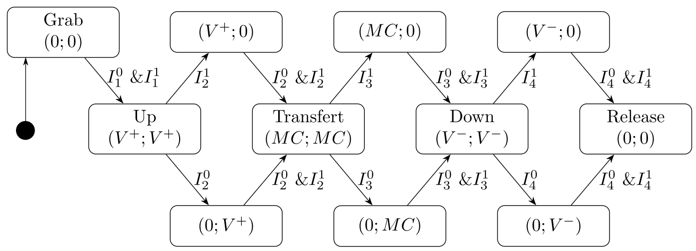

Fig. 3 State machine diagram for the forward trajectory

Another drawback is load oscillation, which can be mitigated by using 2 cables per drum arranged to form a parallelogram mechanism.

4 Experiments

In order to measure our robot's energy consumption, we built a prototype of our solution. For practical and time reasons, we have not implemented the cable drum switches system, but we emulated it by reading the motors' encoder pulses with two Phidget Encoder boards.

4.1 Hardware

The diagram of the hardware experimental setup is shown in Fig. 4. The angular velocity of the control drum cam is managed by a Phidget 1065 board, and its power supply can be cut off using relay $RS1$. Note that this board is used only as a convenience to control the speed of the control drum, but in normal operation, we will apply a constant tension to the motor, and this board will no longer be necessary. To grasp the object, relay $RS0$ activates a radio transmitter, which in turn triggers a radio-controlled relay on the platform, allowing a solenoid to be powered by an onboard battery. The cable motors (M0 and M1) are controlled by two Sabertooth motor speed controller cards (MC0 and MC1), which receive their input tensions from the potentiometers actuated by the command drum cam or by constant tensions for the approximate vertical motions. Switching between these control modes is achieved by using the emulated relays system. Unlike the experimental prototype, the real robot would not present any electronic boards besides the two Sabertooth MC boards.

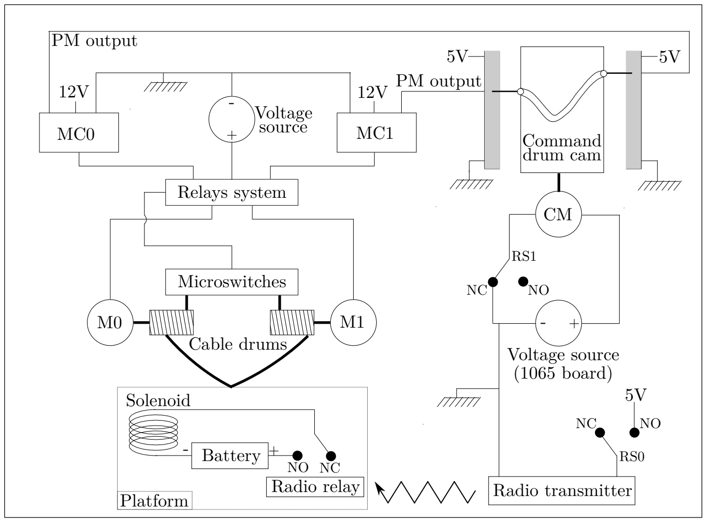

Fig. 4 Diagram of the experimental setup (CM: control motor, PM: potentiometer)

4.2 Trajectory

To evaluate the performance of the proposed prototype, we conducted a series of 30 pick-and-place cycles while handling a 509 g payload. The trajectory shown in Fig. 1 is executed with a cycle time of 40s (forward and return). A video of the experiment is available on the Hephaistos website. During this experiment, the values of the motor encoders were recorded and an a posteriori processing of these data allows us to obtain the load motion by using the forward kinematics model of the CDPR. Fig. 5 shows the trajectory obtained over the 30 PP cycles. As expected, the trajectory deviates from the nominal reference during the transfer phase due to our open-loop control strategy. However, despite this drift, the pick and place positions are reached with an accuracy better than one millimeter.

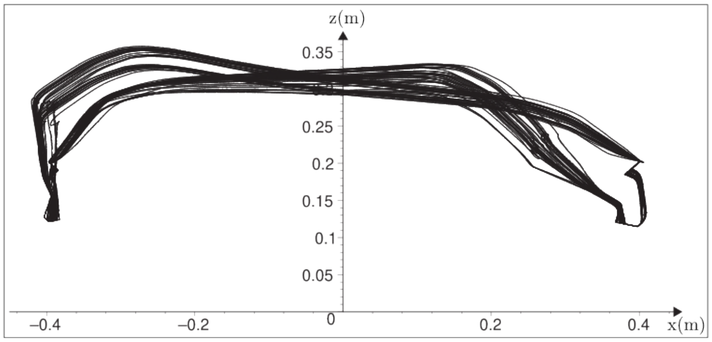

Fig. 5 Effective trajectory for 30 PP cycles

4.3 Energy consumption

During this experiment, we also recorded the power consumption using an accurate power meter which measures instantaneous power (W) and the cumulative energy consumption with a resolution of 1 Wh. When the robot is stationary, the measured power, with the emulated relays system, is 10.4 W. However, it could be even smaller with the real relay system (around 7 W).

To estimate the average required power during pick-and-place operation, we recorded the time values at which the measured energy level changed by 1 Wh during robot motion.

Table 1 summarizes the results obtained for 30 PP cycles. The first four columns report the measurements recorded during robot operation and computed average required power and the fifth column the results for the 30 cycles which ended at $t = 1199$s, for an extrapolated total consumed energy of 4.763 Wh. From this result, we deduce an average power consumption of **14.3 W** during pick-and-place operation.

Measured energy consumed (Wh)	1	2	3	4	*4.763*
Measured time (s)	252	503	755	1007	1199
Computed average power (W)	14.286	14.314	14.305	14.300	14.292

Table 1 Experimental measures. The first four columns provide data recorded during operation and the fifth the final results when the 30 PP cycles have been completed.

To compare the efficiency of the proposed control architecture, several PP cycles were first performed using a standard control algorithm running on a Fit-PC2 (5 ms loop period), yielding an average power consumption of 16.6 W. These results were subsequently compared to manufacturer data for industrial ADEPT robots[1] [2] [3] performing a standard cycle with a 0.1 kg payload. To ensure a fair comparison of total system consumption, an offset of 120 W was added to the industrial data to account for the SmartController EX[4].

When normalized by distance, the energy required to make a full cycle for the industrial robots ranged between 258 and 339 J/m at a 0.1 kg payload. In contrast, the proposed robot consumed 286 J/m under classical computer control and achieved **246 J/m using the open-loop strategy**, notably while carrying a significantly higher payload (0.5 kg). Further optimization of the cycle time—tested over a 3.5 m span at 0.12 m/s with 0.5 kg—reduced the normalized energy consumption to **119 J/m**, less than half of the energy required by an industrial robot.

Differences in operating speeds, payloads and distance may partly explain the observed variations, but these results demonstrate that the proposed strategy significantly enhances energy efficiency for large workspace and high-payload pick-and-place operations.

4.4 Workspace

Another advantage of our approach lies in its ability to handle heavy loads over large workspaces. To illustrate this capability, a pick-and-place trajectory spanning 5 m is currently being investigated. However the height of the supporting masts should be adjusted. Indeed having higher masts improve the energy efficiency as the horizontal parts of the cable tensions, that play a negative role for efficiency, are decreasing but on the other hand the sensitivity of the horizontal positioning errors with respect to cable length errors increases so that a compromise has to be found. In our case the height of the masts is limited by the ceiling so that the output points A have a height of 2.3 m and our preliminary test have already shown a low energy consumption on a 3.5 m trajectory that will be very difficult to perform with classical PP robots.

5 Conclusion

A "green" robot for PP operation was presented, at low or moderate speeds, using CDPR and an innovative control system without any computer and a

[1] Omron, Quattro 650AL User's Guide,accessed January 12, 2026.
[2] Adept, Adept Cobra s600 User's Guide,accessed January 12, 2026.
[3] Omron,Viper 650 User's Guide,Automation website,accessed January 12, 2026.
[4] Omron, SmartController EX data, accessed March 9, 2026

single control board with the trajectory encoded on a mechanical drum that reflects the desired trajectory. The use of this robot leads to a drastic decrease of energy consumption for PP operation compared to commonly used robots, together with a minimal use of electronic resources.

However, this approach also presents several limitations. In particular, encoding the trajectory mechanically makes the system less flexible than conventional digitally controlled robots, as modifying the trajectory requires redesigning and replacing the drum. Moreover, the long-term performance of the system must account for mechanical wear of the drum and sliders over a large number of operating cycles. Despite these limitations, the concept remains attractive for applications involving repetitive tasks over large workspaces and with significant payloads.

The concept can be extended to have spatial PP operations using either a 3-1 or 4-1 CDPR while keeping the advantage of being easy to maintain, having possibly a large workspaces and/or the ability to move heavy loads. Another possible extension will be to get rid of any electronic board by using directly the motion of the sliders to actuate the cable drum, getting back to the automaton principle while keeping the possibility of programming the system.

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