



Design and Fabrication of a Robotic Arm for Pick-and-Place Industrial Applications

Korinna Ramasubbu

Department of Technology and Innovation Management, Peninsula Institute of Engineering Studies, Malaysia

korinna.ramasubbu@pies-my.edu

Peer Review Information

Submission: 21 Jan 2021

Revision: 07 Feb 2021

Acceptance: 22 March 2021

Keywords

Robotic arm, Pick-and-place, Industrial automation, Inverse kinematics, End-effector

Abstract

This methodology paper presents a systematic design-and-fabrication framework for a compact articulated robotic arm intended for repetitive pick-and-place operations in small and medium industrial workcells. The proposed architecture uses four controlled rotary joints and a two-finger parallel gripper, with actuator selection based on payload, link mass, static torque, reach, and a safety factor. Mechanical parts are modeled before fabrication, while forward and inverse kinematics define the end-effector position and joint commands. The control sequence is organized around home, approach, grasp, lift, transfer, lower, release, and return states. A low-cost microcontroller and servo-based actuation are adopted to keep the prototype accessible while preserving industrially relevant design principles. The validation plan evaluates reachable workspace, positioning error, repeatability, payload margin, gripper holding capability, and cycle time. Analytical verification for a representative 0.50 kg payload and 450 mm reach indicates that the proposed sizing method can maintain an adequate torque margin at the shoulder joint and can support a repeatable pick-and-place sequence when backlash and structural deflection are controlled. The framework integrates mechanical design, kinematic modeling, actuator sizing, fabrication, programming, and performance verification into a reproducible step-by-step process suitable for laboratory prototyping and future industrial scaling.

Introduction

Industrial automation increasingly depends on manipulators that can transfer components between fixtures, conveyors, inspection stations, and packaging locations with consistent timing and reduced operator exposure to repetitive work. Pick-and-place is one of the fundamental manipulation tasks because it combines reaching, grasping, payload transfer, placement, and return motion in a single cycle. The design challenge is not simply to make a robot move; it is to create a mechanical and control system whose reachable workspace, payload, stiffness, gripper force, actuator torque, and positioning accuracy are mutually compatible. Low-cost arms are

especially relevant for teaching laboratories, small manufacturers, and proof-of-concept production cells where commercial industrial robots may be unnecessarily expensive or oversized. Kato et al. demonstrated that simplified, low-cost manipulators can be configured for lightweight pick-and-place tasks, while Kim and Song showed that mechanical counterbalancing can reduce actuator demand in economical robot arms [1], [2].

A practical robotic arm must also be designed around kinematic feasibility. For a serial manipulator, forward kinematics predicts the end-effector pose from known joint angles,

whereas inverse kinematics computes the joint variables required to reach a specified target. Al Tahtawi et al. implemented inverse kinematics on a small-scale 3-DOF arm and reported that coordinate-based motion can be embedded in a microcontroller-oriented pick-and-place platform [3]. Beyond kinematics, the end-effector strongly determines whether the task succeeds. Reviews of industrial grippers emphasize that gripping mechanism, object geometry, surface condition, payload, required speed, and compliance must be selected as a system rather than as an isolated component [4], [5]. Accordingly, the present work develops a methodology for a compact four-axis arm with a simple parallel gripper and a design payload of 0.50 kg.

The contribution of this paper is a reproducible engineering sequence that links requirement definition, CAD design, torque calculation, kinematic modeling, fabrication, electronics integration, motion programming, and validation. The focus is methodology rather than unsupported empirical claims. Therefore, the Results section reports analytical design checks and clearly identified validation targets; actual measured values should replace these targets when a physical prototype is tested. This approach is consistent with lightweight prototype development reported by Gutiérrez et al., where structural and manufacturing considerations were integrated early in the design process [6].

Literature Review

Research on economical manipulators shows a recurring trade-off between mechanical simplicity and positioning performance. Kato et al. proposed a low-cost flexible manipulator for lightweight pick-and-place tasks using a small number of actuators, illustrating the feasibility of task-specific arm architectures [1]. Kim and Song developed a 3-DOF counterbalanced arm in which gravity compensation reduced the torque required from the actuators, an important principle when low-cost motors are used [2]. Gutiérrez et al. later presented a lightweight robot-arm prototype and highlighted the role of design-for-manufacture, component mass reduction, and structural verification in improving manipulator practicality [6]. These works support the use of short, lightweight links and conservative actuator sizing for the present prototype.

Kinematic control has received comparable attention. Al Tahtawi et al. designed a small-scale robot arm for pick-and-place operation and

embedded an inverse-kinematics method in an Arduino Mega controller [3]. Their results showed that the arm could move according to target coordinates, while also revealing that mechanical and servo limitations create nonzero position error. Such findings justify including calibration and repeatability tests instead of relying on mathematical kinematics alone. For production-like conveyor tasks, Han et al. showed that sequence planning can materially influence throughput; their optimization study found that better pick ordering can reduce overall execution time relative to simple heuristics [7]. Thus, cycle time in the proposed methodology is treated as a system-level result of both mechanical speed and motion sequencing.

Gripper selection is equally important. Tai et al. reviewed robotic gripper technologies and noted the wide range of mechanical, vacuum, magnetic, and soft-gripping approaches available for different object classes [4]. Birglen and Schlicht statistically examined industrial grippers and reinforced the importance of matching gripping method to application constraints [5]. For compliant manipulation, Zhou et al. developed a soft robotic gripper with enhanced object adaptation and grasping reliability, demonstrating the benefit of compliance when geometry varies [8]. Su et al. reported a high-payload proprioceptive hybrid gripper that combines compliant actuation with sensing, showing a path toward more intelligent end-effectors [9]. For the present arm, however, a rigid parallel two-finger gripper is selected because the target objects are assumed to be regular prismatic or cylindrical components and the priority is low-cost fabrication.

Industrial pick-and-place reliability also depends on detecting failures rather than assuming every grasp succeeds. Zhu et al. combined visual and proprioceptive cues for failure detection and recovery during pick-and-place under partial occlusion [10]. Their work motivates the inclusion of simple confirmation logic in the control sequence, even when the first prototype uses only limit switches or grip-position checks. Velineni et al. designed a pneumatic four-jaw gripper and emphasized the relationship between gripper geometry, actuation pressure, and application-specific holding requirements [11]. Collectively, the literature indicates that a robust methodology should address four tightly coupled layers: structural design, kinematics, actuation and gripping, and task-level validation. The present framework combines these layers in a single fabrication-oriented procedure using references published no later than 2021.

Methodology

The proposed research methodology is organized as a sequential design-build-test workflow. Each step produces parameters or hardware outputs

needed by the following step, and validation results are fed back into the design if the acceptance criteria are not met. Figure 1 summarizes the overall process.



Figure 1. Step-by-step methodology for design, fabrication, control integration, and validation.

Step 1 - Define design requirements. The target application is the transfer of small industrial parts between two fixed stations. A design payload of 0.50 kg is selected, excluding the gripper mass. Required horizontal reach is approximately 450 mm, useful vertical travel is at least 250 mm, base rotation is 180 degrees, and the desired nominal cycle time is below 8 s for a simple point-to-point transfer. The arm should be bench-mounted, electrically powered, inexpensive to fabricate, and capable of repeated operation without permanent link deformation. A factor of safety of at least 1.5 is used for actuator torque and structural sizing.

Step 2 - Select configuration and mechanical layout. A serial articulated layout with base rotation, shoulder pitch, elbow pitch, and wrist pitch is adopted because it provides an adequate workspace with fewer components than a full six-axis industrial manipulator. Link lengths are selected as 220 mm for the upper arm and 200 mm for the forearm, with a 70 mm wrist/gripper offset. Aluminum alloy flat or box sections are preferred for the primary links because they reduce moving mass while remaining easy to machine and drill. Bearings or polymer bushings are positioned at the shoulder and elbow to reduce friction and joint play. The base plate is stiffened to prevent tilt during maximum-reach lifting.

Step 3 - Model kinematics and workspace. Coordinate frames are assigned using the Denavit-Hartenberg convention. For planar shoulder-elbow motion, the end-effector center point can be approximated by $x = L_1 \cos(\theta_2) + L_2 \cos(\theta_2 + \theta_3)$ and $z = h + L_1 \sin(\theta_2) + L_2 \sin(\theta_2 + \theta_3)$, while base angle θ_1 determines the horizontal direction. Inverse kinematics determines θ_2 and θ_3 for each target coordinate. Solutions outside joint limits or near singular configurations are rejected. A numerical workspace sweep is then used to confirm that both pick and place coordinates are reachable with a safe approach

height. The coordinate-based philosophy follows the small-scale implementation reported in [3].

Step 4 - Size actuators using worst-case torque. The shoulder is treated as the most heavily loaded joint. Static torque is estimated from the moments of the payload, gripper, forearm, and upper-arm masses about the shoulder. For example, with a 0.50 kg payload located approximately 0.42 m from the shoulder, the payload moment alone is about 2.06 N m. Adding link and gripper moments gives a representative total static shoulder demand near 3.8 N m. Applying a factor of safety of 1.5 gives a minimum target actuator capability of approximately 5.7 N m before dynamic effects. The elbow is sized by the same method using the downstream masses only. High-torque metal-gear servos or geared DC/stepper actuators with equivalent torque ratings are selected. This conservative approach is intended to prevent stall and excessive heating.

Step 5 - Design the gripper and fabricate components. A two-finger parallel gripper is selected for regular parts. The fingers use replaceable rubber pads to increase friction and reduce surface damage. Required normal force is estimated from $F_N \geq mg/(2\mu)$, where μ is the pad-object coefficient of friction; a safety multiplier is then applied for acceleration and uncertainty. Mechanical components are produced by CNC cutting, laser cutting, or manual machining depending on facility availability. Joint holes are drilled using a common datum to limit alignment error. Fasteners are secured with locking nuts or thread-locking compound, and cable paths are kept away from pinch points. Gripper geometry is treated as application-specific, consistent with the selection principles discussed in [4], [5], and [11].

Step 6 - Integrate electronics and control hardware. A microcontroller provides joint commands, digital input monitoring, and the finite-state pick-and-place sequence. Each actuator is powered from a regulated supply sized for simultaneous starting current rather

than from the logic-board regulator. A common ground is maintained between controller and actuator supply. Emergency stop, home switch, and optional object-presence switch are included. Joint zero offsets are stored after calibration. The wiring architecture separates signal lines from high-current motor wiring to reduce electrical noise. More advanced prototypes may add force or pressure feedback inspired by proprioceptive gripper studies [9], [10].

Step 7 - Program the pick-and-place sequence. The motion is implemented as a finite-state machine: HOME -> APPROACH PICK -> DESCEND -> GRASP -> LIFT -> TRANSFER -> DESCEND PLACE -> RELEASE -> RETRACT -> HOME. Joint trajectories use bounded speed and acceleration to reduce vibration. The controller first verifies that computed angles fall inside joint limits; it then commands the joints in a coordinated sequence and inserts a short settling interval before grasp and release. For moving-conveyor extensions,

object order and timing can be optimized as discussed by Han et al. [7], but the baseline prototype uses fixed stations to isolate mechanical and positioning performance.

Step 8 - Validate performance. Validation consists of five tests: (i) workspace verification at boundary points; (ii) payload test from 0.10 to 0.50 kg; (iii) positioning accuracy using commanded versus observed target coordinates; (iv) repeatability over at least 30 identical cycles; and (v) cycle-time measurement from the start of approach to completion of placement. A successful grasp is recorded only when the object is lifted, transferred, and released at the target without slip. The prototype is accepted when it completes the defined task without stall, structural interference, or loss of object and remains within the selected error and cycle-time limits. Failure events are logged so that mechanical backlash, gripper slip, and command timing can be distinguished, consistent with the failure-aware perspective in [10].

Table 1. Proposed design specifications and acceptance criteria

Parameter	Design value	Verification method	Acceptance criterion
Degrees of freedom	4 + gripper	Joint command check	All programmed joints responsive
Payload	0.50 kg	Incremental lift test	No stall or object slip
Maximum reach	~450 mm	Geometric/workspace test	Pick and place coordinates reachable
Shoulder torque target	≥ 5.7 N m	Static torque calculation	Safety factor ≥ 1.5
Positioning accuracy target	$\leq \pm 10$ mm	Coordinate measurement	Mean absolute error within limit
Repeatability target	≤ 5 mm spread	30 repeated cycles	Maximum spread within limit
Nominal cycle time	< 8 s	Stopwatch/controller log	Average below target
Grasp success	$\geq 95\%$ target	30-cycle task test	At least 29 successful transfers

Results

Because this paper defines a methodology rather than reporting a completed laboratory campaign, results are limited to analytical design verification and explicit prototype targets. The link dimensions provide a nominal radial reach of approximately 420 mm before the wrist offset, satisfying the 450 mm-class workspace objectives when the end-effector length is included. The torque calculation identifies the shoulder as the critical joint. A representative static requirement of about 3.8 N m becomes 5.7 N m after applying the 1.5 safety factor; therefore, an actuator below this continuous or equivalent geared output rating should not be used for the specified payload. The same calculation also

shows why reducing forearm and gripper mass is more effective than only increasing motor size, because each downstream mass contributes a moment proportional to its distance from the shoulder.

The kinematic model provides a direct method for generating the joint commands for fixed pick and place locations. At every target, inverse-kinematic solutions must be filtered by joint limits and then checked for collision with the work surface. The literature indicates that practical coordinate error can remain even when the mathematical solution is correct; Al Tahtawi et al. reported nonzero position error in a small-scale inverse-kinematics arm [3]. Consequently, the proposed validation uses calibration offsets

and repeated coordinate measurement rather than assuming ideal geometry. A design target of ± 10 mm is considered realistic for a low-cost

servo prototype and can later be tightened by using encoders, stiffer joints, or better gearboxes.

Table 2. Analytical verification and prototype validation targets

Performance item	Analytical/target value	Interpretation	Status at methodology stage
Radial reach	~ 420 mm + wrist offset	Sufficient for fixed two-station transfer	Verified geometrically
Shoulder static torque	~ 3.8 N m	Largest joint load occurs near full extension	Calculated
Shoulder design torque	≥ 5.7 N m	Includes 1.5 safety factor	Selection criterion
Positioning accuracy	$\leq \pm 10$ mm	Suitable initial low-cost prototype target	To be measured
Repeatability	≤ 5 mm spread	Needed for stable placement	To be measured
Grasp success	$\geq 95\%$	Requires adequate finger friction and alignment	To be measured
Cycle time	< 8 s	Baseline fixed-point pick-and-place task	To be measured

The gripper analysis confirms that grip force must be set from object mass and friction rather than from finger travel alone. A rigid two-finger gripper is adequate for the defined regular workpieces, while compliant or proprioceptive grippers would be preferable if the object population becomes irregular or fragile [8]-[10]. The planned cycle-time test should also separate transfer time from settling and gripping delays. This distinction is important because industrial throughput can be improved by better sequencing as well as by higher actuator speed [7]. Overall, the analytical checks indicate that the proposed four-axis architecture is feasible for a 0.50 kg classroom or light-industrial prototype provided that the shoulder actuator meets the torque criterion and joint backlash is controlled.

Conclusion and Discussion

This paper developed a complete methodology for designing and fabricating a robotic arm for pick-and-place industrial applications. The procedure begins with payload, reach, accuracy, and cycle-time requirements; proceeds through configuration selection, kinematic modeling, torque calculation, gripper design, and fabrication; and concludes with electronics integration, finite-state motion programming, and performance validation. The methodology deliberately links mechanical and control decisions. For example, longer links increase workspace but also increase shoulder torque and deflection, while faster commands may reduce cycle time but increase vibration and the chance of grip loss. These coupled trade-offs are central

to low-cost manipulator design and are consistent with previous work on economical and lightweight robot arms [1], [2], [6]. The selected four-axis architecture is appropriate for repeated transfer of simple parts between known locations. Inverse kinematics provides coordinate-based motion [3], while the gripper is sized using object geometry, friction, and load requirements informed by established gripper research [4], [5], [11]. Reliability should not be evaluated only from whether the arm reaches the target; grasp confirmation and failure logging are also required, as demonstrated by failure-aware pick-and-place research [10]. For future development, the prototype can be extended with encoder feedback, machine vision, conveyor tracking, compliant fingertips, force sensing, and collision-aware trajectory planning. These additions would allow the same basic hardware to progress from a fixed-position demonstration toward flexible industrial material handling. A key limitation is that the present Results section contains analytical design verification and test criteria rather than fabricated laboratory measurements. Before the work is submitted as an empirical experimental paper, the specified tests should be performed on the physical arm and the target values in Table 2 should be replaced by measured mean, maximum error, standard deviation, success rate, and cycle-time data. Used in this way, the methodology provides a transparent basis for reproducible prototype development and for comparing successive mechanical and control revisions.

References

G. Kato, D. Onchi, and M. Abarca, "Low-cost flexible robot manipulator for pick and place tasks," in 2013 10th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI), 2013, pp. 677–680. DOI: 10.1109/URAI.2013.6677451.

H. S. Kim and J. B. Song, "Low-cost robot arm with 3-DOF counterbalance mechanism," in 2013 IEEE International Conference on Robotics and Automation (ICRA), 2013, pp. 4183–4188. DOI: 10.1109/ICRA.2013.6631168.

R. Al Tahtawi, M. Agni, and T. D. Hendrawati, "Small-scale Robot Arm Design with Pick and Place Mission Based on Inverse Kinematics," *Journal of Robotics and Control*, vol. 2, no. 6, pp. 469–475, 2021. DOI: 10.18196/jrc.26124.

K. Tai, A.-R. El-Sayed, M. Shahriari, M. Biglarbegian, and S. Mahmud, "State of the Art Robotic Grippers and Applications," *Robotics*, vol. 5, no. 2, Art. 11, 2016. DOI: 10.3390/robotics5020011.

L. Birglen and T. Schlicht, "A statistical review of industrial robotic grippers," *Robotics and Computer-Integrated Manufacturing*, vol. 49, pp. 88–97, 2018. DOI: 10.1016/j.rcim.2017.05.007.

S. C. Gutiérrez, R. Zotovic, M. D. Navarro, and M. D. Meseguer, "Design and manufacturing of a prototype of a lightweight robot arm," *Procedia*

Manufacturing, vol. 13, pp. 283–290, 2017. DOI: 10.1016/j.promfg.2017.09.072.

S. D. Han, S. W. Feng, and J. Yu, "Toward Fast and Optimal Robotic Pick-and-Place on a Moving Conveyor," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 446–453, 2020. DOI: 10.1109/LRA.2019.2961605.

J. Zhou, S. Chen, and Z. Wang, "A Soft-Robotic Gripper With Enhanced Object Adaptation and Grasping Reliability," *IEEE Robotics and Automation Letters*, vol. 2, no. 4, pp. 2287–2293, 2017. DOI: 10.1109/LRA.2017.2716445.

Y. Su et al., "A High-Payload Proprioceptive Hybrid Robotic Gripper With Soft Origami Actuators," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 3003–3010, 2020. DOI: 10.1109/LRA.2020.2974438.

F. Zhu et al., "Failure Handling of Robotic Pick and Place Tasks With Multimodal Cues Under Partial Object Occlusion," *Frontiers in Neurorobotics*, vol. 15, Art. 570507, 2021. DOI: 10.3389/fnbot.2021.570507.

P. Velineni, J. Suresh, C. Naveen Kumar, and M. Suresh, "Design of Pneumatic Gripper for Pick and Place Operation (Four Jaw)," *International Research Journal of Multidisciplinary Technovation*, vol. 2, no. 2, pp. 1–8, 2020. DOI: 10.34256/irjmt2021.