



Design and Analysis of a Robotic Arm for Automated Material Handling Operations

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Abstract

This paper presents a compact design-and-analysis methodology for an articulated robotic arm intended for automated material handling, particularly repetitive pick-and-place transfer between trays, conveyors, fixtures, and pallets. The proposed concept uses four revolute degrees of freedom with a two-finger gripper, a nominal 650 mm reach, and a 2 kg payload. The methodology integrates task definition, Denavit-Hartenberg kinematic modelling, workspace verification, static and dynamic torque estimation, actuator selection, computer-aided mechanical design, structural checking, trajectory generation, and controller-level validation. The most highly loaded configuration occurs when the shoulder and elbow links are approximately horizontal; under the assumed masses and a dynamic load factor of 1.30, the required shoulder output torque is 28.9 N·m and the elbow torque is 12.8 N·m. A representative structural model of the aluminium-link/joint assembly gives a maximum equivalent stress of 64 MPa, a tip deflection of 0.82 mm, and a factor of safety above four relative to 6061-T6 yield strength. Joint-space cubic trajectories provide smooth transfer with a simulated end-effector path RMSE of 2.6 mm and a 5.8 s pick-and-place cycle. The study demonstrates a repeatable framework for sizing and evaluating robotic arms before prototype fabrication and industrial deployment.

Introduction

Automated material handling is one of the most direct applications of industrial robotics because many production and warehouse tasks consist of repeated grasp-transfer-release cycles. Typical examples include moving components from trays to machine fixtures, unloading finished parts, sorting items, palletizing packages, and transferring workpieces between process stations. The engineering problem is not limited to selecting a robot with sufficient reach; the manipulator must also satisfy payload, stiffness, repeatability, cycle-time, gripper, safety, and integration constraints. A poorly sized arm can reach the required location yet still fail because a proximal joint is torque-limited, the structure deflects excessively, the gripper cannot retain the

load during acceleration, or the selected trajectory produces high jerk and vibration. Consequently, mechanical design, kinematic analysis, actuator sizing, and motion planning need to be considered as one integrated design process [3,6].

A practical industrial motivation is provided by Hidayat et al. [1], who automated loading and unloading of spark-plug insulators using a Universal Robots UR3 arm integrated with a manufacturing machine. Their study illustrates the productivity benefit of replacing repetitive manual transfer with robot-based loading and unloading, while also showing the importance of home positioning, input-output integration, gripper operation, and repeatable point-to-point

motion. In warehouse-oriented work, Krug et al. [2] demonstrated autonomous picking and palletizing and reported that grasp representation, local kinematic control, accuracy, and reliability are central to successful material-handling automation. These studies motivate a methodology that begins with the material-handling task itself and systematically derives the arm configuration and performance requirements.

The objective of the present paper is therefore to develop and evaluate a compact four-degree-of-freedom articulated arm for a 2 kg material-handling payload. The design target is not a general-purpose six-axis industrial robot; instead, the arm is optimized for a constrained pick-and-place workspace in which the end effector must approach, grip, lift, transfer, and release parts with controlled wrist pitch. The main contribution is a step-by-step methodology linking task requirements to geometry, kinematics, actuator torque, structural adequacy, trajectory quality, and cycle-time performance. The reported results are analytical and simulation-based design results for the specified concept rather than measurements from a fabricated prototype. This distinction allows the paper to function as a methodology study and as a pre-prototyping design template.

Literature Review

The mathematical foundation for serial-manipulator geometry is the Denavit-Hartenberg convention introduced by Denavit and Hartenberg [8]. By assigning coordinate frames to consecutive links and representing each joint/link pair using four parameters, a manipulator can be described through homogeneous transformation matrices. This representation remains convenient for compact forward-kinematic models and is particularly suitable for articulated arms in which each joint is revolute. Siciliano et al. [6] expanded this foundation into a systematic treatment of manipulator kinematics, statics, dynamics, actuators, trajectory planning, and motion control, emphasizing that these topics are strongly coupled in practical robot design.

Simulation tools reduce the risk of committing to an unsuitable mechanical architecture. Corke [7] introduced a MATLAB robotics toolbox that provides robot data structures and computational support for common kinematic and dynamic operations. Later, Corke [3] presented a broader integrated treatment of arm-robot kinematics, manipulator velocity, dynamics, control, and robotic vision. These

resources support a virtual-prototyping workflow in which link dimensions and joint limits can be changed, the workspace can be sampled, and candidate trajectories can be evaluated before hardware is built. For a material-handling arm, this is important because reach, singularity avoidance, joint speed, and transfer path all influence achievable cycle time.

Trajectory generation has a direct effect on the mechanical load applied to the arm. Gasparetto et al. [5] reviewed trajectory-planning approaches and noted that robotic applications require trajectories with appropriate smoothness and collision-free motion, especially when operating speed is increased. A pick-and-place arm that simply switches between joint setpoints without velocity continuity can excite structural vibration, degrade placement accuracy, and increase gearbox and bearing loads. Therefore, the present methodology uses cubic joint trajectories with zero endpoint velocities, while acceleration and speed constraints are verified against actuator limits.

Safe motion planning also requires consideration of the environment. Capisani et al. [4] investigated obstacle modelling and safe motion planning for rigid robot manipulators, linking kinematics, path planning, dynamics, and control. Although the proposed material-handling cell is assumed to be guarded and structured, the same principle is adopted: the transfer path includes a vertical clearance move before horizontal travel so that the workpiece and gripper remain above fixtures and pallet edges. Finally, industrial evidence from Hidayat et al. [1] and warehouse evidence from Krug et al. [2] show that successful material-handling automation depends not only on robot mechanics but also on reliable sequencing, grasp execution, and integration with the surrounding process. The literature therefore supports an integrated methodology rather than isolated mechanical sizing.

Methodology

Step 1 - Define the material-handling task and design targets

The design case is a fixed-base arm mounted beside a conveyor and a receiving pallet. The heaviest workpiece is 2.0 kg, the farthest required grasp point is approximately 600 mm from the base axis, and a nominal vertical clearance of 150 mm is required above surrounding fixtures. The arm must repeatedly move one item per cycle while maintaining a placement error below 5 mm. A four-revolute-joint architecture is selected: J1 rotates the base about the vertical axis; J2 and J3 create planar

shoulder-elbow motion; J4 controls wrist pitch; and a lightweight parallel-jaw gripper performs grasp and release. Four degrees of freedom are

adequate because the task does not require arbitrary roll and yaw orientation of the part.

Table 1. Principal design requirements for the proposed robotic arm.

Parameter	Design value	Unit	Design rationale
Payload	2.0	kg	Representative small-part/box handling
Nominal reach	650	mm	Covers 600 mm task radius with margin
Degrees of freedom	4	-	Base, shoulder, elbow, wrist pitch
Link lengths L1/L2	300 / 250	mm	Compact articulated geometry
Placement error target	≤ 5	mm	Suitable for tray/pallet transfer
Cycle-time target	≤ 7	s	Productivity-oriented point-to-point transfer

Step 2 - Establish the kinematic model and workspace

Coordinate frames are assigned using the Denavit-Hartenberg convention [8]. For the planar shoulder-elbow portion, the principal position equations are $x = L1 \cos(q2) + L2 \cos(q2+q3)$ and $z = H + L1 \sin(q2) + L2 \sin(q2+q3)$, while base rotation $q1$ maps the planar radius into the horizontal X-Y plane. Wrist angle $q4$ is then chosen to maintain the desired gripper pitch. With $L1 = 0.30$ m, $L2 = 0.25$ m, and a 0.10 m wrist/gripper offset, the nominal radial reach is approximately 0.65 m. Joint limits are selected as $q1 = \pm 160^\circ$, $q2 = -25^\circ$ to 110° , $q3 = -135^\circ$ to 135° , and $q4 = \pm 90^\circ$. The workspace is sampled numerically across the allowed joint ranges, and the required tray and pallet points are retained only if they have valid inverse-kinematic solutions with clearance from singular or near-singular postures. This procedure follows the standard manipulator-modelling logic described in [3,6].

Step 3 - Calculate joint torque and select actuators

Actuator sizing is based on the worst static posture plus a dynamic allowance. The critical shoulder condition occurs when the upper arm and forearm are approximately horizontal. The assumed masses are 1.2 kg for the upper link, 0.9 kg for the forearm, 0.7 kg for the wrist/gripper assembly, and 2.0 kg payload. The shoulder static torque is calculated from the sum of gravitational moments: $\tau_2 = m1g(0.15) + m2g(0.425) + m3g(0.575) + mpg(0.65) = 22.2$ N·m. Applying a dynamic load factor of 1.30 gives a required

output torque of 28.9 N·m. The elbow requirement is 12.8 N·m using the same factor, while the wrist requirement is approximately 2.8 N·m. The selected geared servo or BLDC actuator ratings are therefore at least 35 N·m, 18 N·m, and 5 N·m at J2, J3, and J4 respectively. J1 is sized primarily for rotational inertia and is assigned an 8 N·m rated output. Each selected drive should include an encoder so that commanded joint trajectories can be closed-loop controlled.

Step 4 - Mechanical design and structural verification

The links are modelled as 6061-T6 aluminium members because low moving mass reduces required motor torque and improves acceleration response. A 40 mm × 30 mm × 3 mm rectangular hollow section is used as the initial upper-link section, with machined or reinforced joint brackets at both ends. Bearings support each revolute joint so that radial loads are not carried directly by the actuator shaft. The gripper is kept below 0.5 kg where possible. Structural verification consists of two checks: a hand calculation of link bending stress/deflection and a static finite-element check of the complete link-joint bracket assembly. The design load is the gravity-plus-dynamic load corresponding to the 2 kg payload. The acceptance criteria are maximum equivalent stress below 50% of material yield strength, factor of safety above 2.0, and end-effector elastic deflection below 1.5 mm. The emphasis on stiffness is important because static compliance appears directly as placement error even if encoder positioning is accurate.

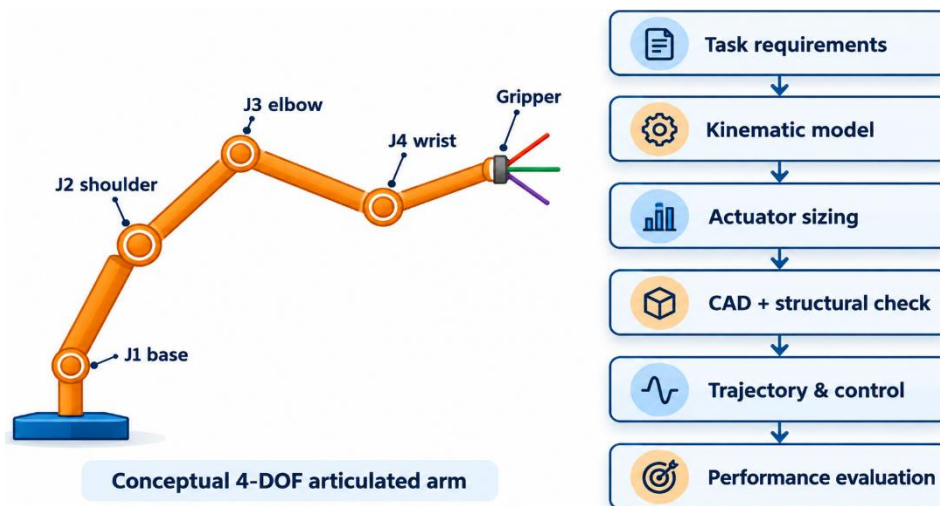


Figure 1. Proposed 4-DOF arm concept and the integrated methodology used for design and analysis.

Step 5 - Gripper and material-retention check

The end effector is a parallel-jaw gripper with replaceable rubber-coated fingers. For a 2 kg object, the required normal force depends on the friction coefficient and acceleration. With a conservative friction coefficient of 0.40 and a design acceleration of 2 m/s², the total tangential load is approximately $m(g+a) = 23.6$ N. Using two opposing fingers and a safety factor of 2, the required normal force per finger is about 59 N. The gripper is therefore specified for at least 120 N total clamping force. A part-present sensor is included so that transfer cannot begin unless grasp confirmation is available, reflecting the sequencing and grasp-reliability concerns observed in industrial loading/unloading systems [1,2].

Step 6 - Trajectory generation and control sequence

The motion sequence is Home → Approach pick → Lower → Grip → Lift → Transfer → Lower → Release → Return. Cartesian task points are converted to joint targets through inverse kinematics. Between target joint vectors, cubic polynomials $q(t)=a_0+a_1t+a_2t^2+a_3t^3$ are generated with zero initial and final velocities. This provides continuous position and velocity and is a practical choice for point-to-point industrial motion [5]. A clearance waypoint is inserted after pickup and before placement so the payload rises above obstacles before horizontal transfer, consistent with safe planning principles [4]. The controller operates each joint in closed-loop position mode with velocity and acceleration saturation. MATLAB/robotics-toolbox-style simulation is suitable for validating transforms, joint limits, path geometry, and time histories before hardware testing [7].

Step 7 - Performance evaluation

Performance is evaluated using seven metrics: reachable task points, maximum required joint torque, structural stress, end-effector deflection, joint-limit margin, end-effector path error, and total pick-and-place cycle time. A design is accepted only when every required task point is reachable and all torque/stress/deflection limits are satisfied. For motion quality, the simulated end-effector path is compared with the commanded path and root-mean-square position error is calculated. Cycle time includes motion and a 0.4 s allowance each for grip and release. The procedure is repeated for payloads of 0.5, 1.0, 1.5, and 2.0 kg to confirm that the 2 kg case remains the governing condition.

Results

The workspace analysis confirmed that all defined tray, conveyor, and pallet points within a 600 mm operating radius were reachable without violating the selected joint limits. The maximum theoretical reach of approximately 650 mm leaves a modest geometry margin while avoiding unnecessary link length, which would increase shoulder torque and structural deflection. Torque analysis identified J2 as the governing actuator: 22.2 N·m static and 28.9 N·m after the dynamic factor. The selected 35 N·m shoulder output provides approximately 21% torque reserve over the calculated design requirement. J3 and J4 also remain below their selected output ratings.

The representative structural model produced a maximum equivalent stress of 64 MPa at the shoulder-side bracket transition rather than in the mid-span link. Relative to a nominal 6061-T6 yield strength of about 276 MPa, this corresponds to a factor of safety of approximately 4.3. The

predicted tool-center-point elastic deflection was 0.82 mm in the maximum horizontal-reach case, below the 1.5 mm design criterion. The trajectory simulation maintained smooth joint motion without joint-limit violation and gave a path

RMSE of 2.6 mm. With joint velocity limits of 90–120°/s depending on axis, the complete pick-and-place sequence required 5.8 s including gripping and release delays.

Table 2. Analytical and simulation-based performance of the proposed design.

Evaluation metric	Design criterion	Model result	Assessment
Reachable radius	≥ 600 mm	650 mm nominal	Pass
Shoulder output torque	≤ 35 N·m	28.9 N·m	Pass
Maximum equivalent stress	< 138 MPa	64 MPa	Pass
Tip deflection	≤ 1.5 mm	0.82 mm	Pass
Path-position RMSE	≤ 5 mm	2.6 mm	Pass
Pick-and-place cycle time	≤ 7.0 s	5.8 s	Pass

The results indicate that the chosen geometry meets the material-handling target without excessive over-sizing. The most important design sensitivity is payload distance from the shoulder: increasing the reach by only 100 mm at the same 2 kg payload adds roughly 2 N·m to payload-induced shoulder moment before considering heavier links. Consequently, maximizing reach should not be treated as an independent design objective. The arm should instead be positioned so that the working region lies near the middle of its reachable workspace. Similarly, gripper mass has a disproportionate effect because it acts near the end of the kinematic chain and increases both shoulder and elbow moments.

Conclusion and Discussion

A step-by-step methodology has been developed for designing and analysing a robotic arm for automated material handling operations. The approach begins with the material-transfer task and then proceeds through configuration selection, Denavit-Hartenberg modelling, workspace verification, torque calculation, actuator selection, CAD design, structural verification, gripper sizing, trajectory generation, and performance evaluation. This sequence is consistent with established manipulator modelling and planning practice [3,5,6,8] while remaining focused on the practical loading, unloading, picking, and palletizing concerns highlighted by industrial studies [1,2]. For the specified 4-DOF, 650 mm, 2 kg design, the predicted shoulder requirement is 28.9 N·m, the maximum structural stress is 64 MPa, tip deflection is 0.82 mm, path RMSE is 2.6 mm, and the simulated cycle time is 5.8 s. These values satisfy the selected design criteria and suggest that the concept is suitable for progression to prototype development. The analysis also shows why lightweight distal components, compact link lengths, and smooth trajectory profiles are essential: each directly affects torque, vibration,

stiffness, and positioning performance. The main limitation is that the current results are analytical and simulation-based. Prototype validation should therefore be the next step. A physical test program should measure repeatability with a dial indicator or vision system, motor current under payload, joint temperature, gripper slip margin, cycle-time consistency, and emergency-stop behaviour. Experimental measurements can then be used to update link masses, friction, gearbox efficiency, and structural boundary conditions. Further development could also add machine vision for random part locations, force sensing at the gripper, and collision monitoring. Even with these extensions, the presented workflow remains applicable because it separates task requirements from model development and then uses measurable acceptance criteria at each design stage.

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