



Design and Analysis of a Pneumatic Pick-and-Place Robotic Arm for Industrial Material Handling

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Peer Review Information

Submission: 27 Jan 2019

Revision: 11 Feb 2019

Acceptance: 26 March 2019

Keywords

Pneumatic robotic arm;
 Pick-and-place; Material
 handling; Pneumatic
 gripper; Industrial
 automation

Abstract

Industrial material handling contains many repetitive pick-and-place operations that require consistent positioning, short cycle times, and safe handling of workpieces. This paper presents a methodology for designing and analysing a compact pneumatic robotic arm intended for repetitive industrial material handling. The proposed system combines a two-joint articulated mechanism, double-acting pneumatic cylinders, a two-jaw pneumatic gripper, a regulated compressed-air supply, directional control valves, and a PLC/microcontroller-based sequence controller. The design procedure begins with task definition and payload selection, followed by workspace sizing, actuator selection, gripper-force calculation, structural load estimation, pneumatic circuit development, and sequence-control design. For a representative design case, a 2 kg payload, 0.6 MPa working pressure, 32 mm cylinder bore, and 0.12 m effective moment arm are used for analytical checks. The calculated cylinder force is approximately 483 N before losses, providing adequate force margin for the selected handling task. Performance is evaluated using payload capacity, grasping reliability, repeatability, cycle time, and pneumatic response. The results presented are design-analysis targets and calculated values rather than measurements from a fabricated prototype. The methodology is intended to provide a practical foundation for a low-cost pneumatic pick-and-place system suitable for repetitive loading, unloading, sorting, and transfer operations.

Introduction

Robotic manipulators are widely used for handling operations because the tasks are repetitive, structured, and readily described by predefined trajectories. Industrial grippers are especially important because they form the interface between the robot and the workpiece. A review of industrial grippers shows that pneumatic two-finger designs are widely represented in industrial applications, with force, stroke, weight, and performance being important selection parameters (Birglen & Schlicht, 2018). General reviews also identify industrial grasping as a mature but continuously evolving area, with

improvements in speed, repeatability, adaptability, and materials (Tai et al., 2016).

Pneumatic actuation is attractive for repetitive handling because compressed air can generate relatively high force with simple cylinders and valves, while the system can be configured for rapid extension and retraction. Michalos et al. (2018) demonstrated a pneumatic gripper for feeding lightweight parts and showed how pneumatic mechanisms can support orientation, grasping, and feeding functions in manufacturing. Pneumatic actuation has also been investigated for complete robotic arms; Ohta et al. (2018) developed a lightweight

pneumatic artificial-muscle arm and demonstrated position-control experiments.

The objective of this study is therefore to establish a clear design methodology for a conventional, workshop-scale pneumatic pick-and-place arm. The study focuses on mechanical sizing, pneumatic force generation, gripper selection, control sequencing, and analytical performance evaluation. The intended result is a compact architecture that can be adapted to industrial transfer and sorting tasks without requiring complex vision or advanced robot dynamics.

Literature Review

Research on robotic end effectors provides the design basis for selecting an appropriate gripper and actuation method. Tai et al. (2016) reviewed robotic grippers across industrial and non-industrial applications and highlighted the importance of grasp geometry, adaptability, speed, and material selection. Birglen and Schlicht (2018) statistically analysed industrial robotic grippers and emphasized measurable parameters such as stroke, gripping force, weight, and a combined performance indicator. These findings support a design process in which the gripper is selected from quantified load and geometry requirements rather than from mechanism type alone.

Michalos et al. (2018) presented a pneumatic gripper capable of orienting and feeding lightweight complex parts. Their work is relevant because it demonstrates that pneumatic mechanisms can do more than simply open and close fingers; they can also support controlled

manipulation in a production environment. Ohta et al. (2018) developed a seven-degree-of-freedom pneumatically powered robotic arm using McKibben artificial muscles, illustrating the potential of pneumatic actuation for lightweight robotic structures. For the present industrial material-handling application, however, conventional cylinders are preferred because they are simpler to size, procure, maintain, and control.

Kaizu et al. (2019) proposed a pneumatic gripper with grasping and pulling-up functions and reported experimental confirmation that the gripper could grasp different objects. Their approach illustrates how pneumatic logic can combine multiple actions using pressure paths and valves. In parallel, robotic pick-and-place research has considered trajectory and timing optimisation; Liu and Wang's 2019 work on moving-conveyor pick-and-place showed that motion planning and object selection can materially affect throughput. Although the present design assumes a stationary pick location, the same principle motivates minimising unnecessary motion and controlling the sequence consistently.

Based on the literature, the main design gap addressed here is not the invention of a new gripper mechanism, but the integration of simple pneumatic actuation, mechanical sizing, force analysis, and sequence control into a compact methodology for industrial material transfer. The proposed architecture deliberately prioritizes simplicity, maintainability, and repeatable operation.

Table 1. Selected literature supporting the design

Reference	Main contribution	Relevance to proposed arm
Tai et al. (2016)	Review of robotic grippers and applications	Gripper selection criteria
Birglen & Schlicht (2018)	Statistical review of industrial grippers	Force, stroke and weight considerations
Michalos et al. (2018)	Pneumatic gripper for feeding/manipulation	Pneumatic grasping and feeding
Ohta et al. (2018)	Pneumatically powered lightweight robotic arm	Pneumatic arm architecture
Kaizu et al. (2019)	Pneumatic grasping and lifting mechanism	Simple pneumatic sequencing
Jiang et al. (2019)	Pick-and-place optimisation on conveyor systems	Cycle-time and trajectory perspective

Methodology

1. Design requirements

The design begins by defining the workpiece and the required transfer path. A representative

workpiece mass of 2 kg is selected, with a target vertical lifting distance of 150–200 mm and a horizontal reach of approximately 300 mm. The arm is assumed to operate indoors in a structured workstation with a regulated air

supply. The design target is repetitive operation with a nominal cycle of approximately 4–5 s,

while maintaining sufficient mechanical and pneumatic safety margin.

Table 1. Design Requirements and Operating Parameters of the Robotic Arm

Parameter	Design value	Purpose
Payload	2 kg	Representative industrial workpiece
Working pressure	0.6 MPa	Nominal regulated pressure
Cylinder bore	32 mm	Joint actuation
Effective moment arm	0.12 m	Torque estimation
Gripper type	2-jaw pneumatic	Parallel grasping
Control	PLC / microcontroller	Sequence automation
Target cycle time	4–5 s	Throughput target

2. Mechanical architecture

The proposed manipulator consists of a rigid base, a first link for vertical lifting, a second link for horizontal reach, and a wrist/end-effector interface. The first two joints are actuated by double-acting pneumatic cylinders through

suitable linkages. A two-jaw pneumatic gripper is attached to the wrist. The frame may be fabricated from aluminium profiles or steel sections depending on payload and required stiffness. Bearings are used at revolute joints to reduce friction and maintain alignment.

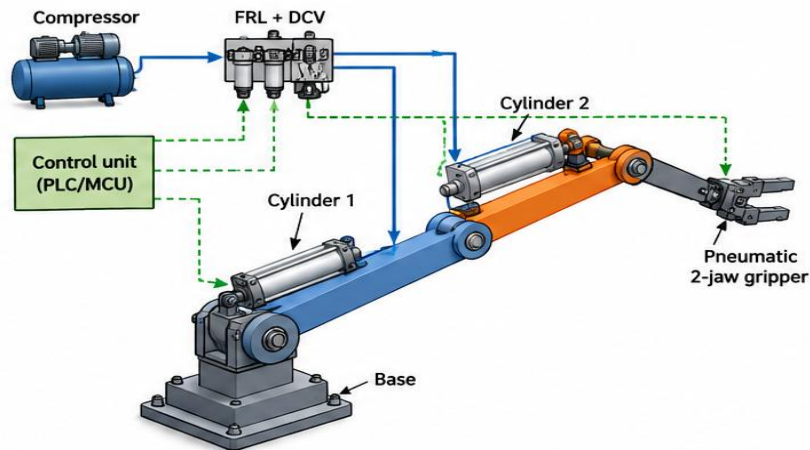


Figure 1. Proposed pneumatic pick-and-place arm architecture.

3. Pneumatic subsystem

The pneumatic subsystem contains a compressor or plant-air connection, filter-regulator-lubricator (FRL) unit, pressure gauge, directional control valves, flow-control valves, cylinders, and the gripper. A regulated pressure is essential because cylinder force is approximately proportional to pressure. Flow-control valves are used to limit actuator speed and reduce impact at the ends of stroke. A pressure regulator also prevents excessive gripping force on fragile components.

4. Actuator and gripper calculations

For a pneumatic cylinder, the ideal extension force is calculated from the pressure acting on the piston area:

$$F = P \times A = P \times (\pi D^2 / 4)$$

For $P = 0.6$ MPa and $D = 32$ mm, the piston area is 804 mm^2 and the ideal extension force is

approximately 483 N. Allowing for friction, valve losses, leakage, and linkage inefficiency, an effective force of about 380–430 N is a practical design estimate. With an effective lever arm of 0.12 m, the corresponding theoretical torque is about 58 N·m, while a conservative usable torque of 45–50 N·m can be considered for preliminary sizing.

The static gravitational torque for a 2 kg payload at a 0.30 m reach is:

$$T_{\text{load}} = m g L = 2 \times 9.81 \times 0.30 \approx 5.89 \text{ N}\cdot\text{m}$$

This simplified calculation indicates a substantial theoretical force margin. In a real prototype, the final margin must also account for link mass, acceleration, joint friction, cylinder orientation, pressure variation, and mechanical losses. The gripper should be sized so that the gripping force exceeds the minimum force needed to resist the workpiece weight and dynamic disturbance without deforming or damaging the workpiece.

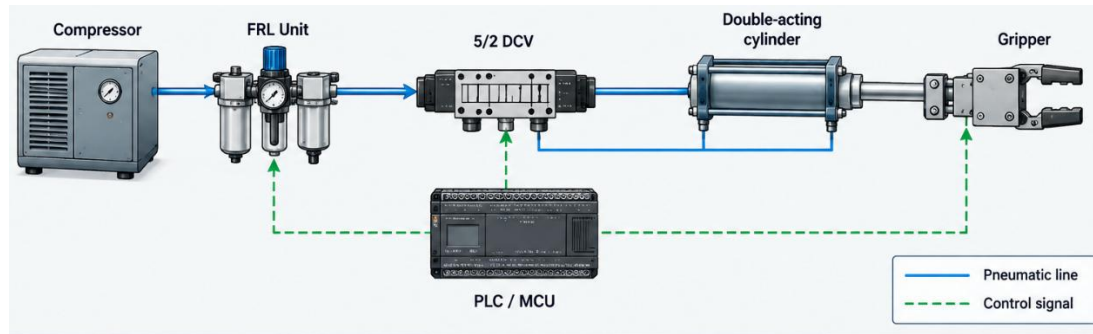


Figure 2. Simplified pneumatic and control circuit.

5. Control sequence

The control program is implemented as a sequential state machine. The sequence is: (1) initialise and verify pressure, (2) move the arm to the pick position, (3) close the gripper, (4) confirm the grasp using a pressure switch or end-position sensor, (5) retract/lift, (6) move to the place position, (7) open the gripper, and (8) return to the home position. Interlocks prevent the next movement if the required pressure or end-position feedback is absent. Emergency-stop logic should remove actuator command signals

and place the pneumatic system in a defined safe state.

Results and Analysis

The following results are analytical design results generated from the stated representative parameters. They are not claimed as experimental measurements from a fabricated prototype. The calculations are intended to establish whether the selected architecture is feasible before fabrication.

Table 2. Calculated Actuator and System Performance Parameters

Metric	Calculated / target value	Interpretation
Cylinder piston area	804 mm ²	For 32 mm bore
Ideal cylinder force @ 0.6 MPa	≈483 N	Before losses
Estimated usable force	≈380–430 N	Allows practical losses
Payload gravitational torque	≈5.89 N·m	2 kg at 0.30 m
Theoretical cylinder torque	≈58 N·m	At 0.12 m lever arm
Target cycle time	4–5 s	Suitable for repetitive handling
Control method	Sequential PLC/MCU	Simple and maintainable

Performance criteria

Five performance criteria are recommended for prototype validation. First, payload capacity should be tested by increasing the workpiece mass until the arm approaches its safe operating limit. Second, grasp reliability should be evaluated by repeating the pick operation at least

50–100 times and recording missed or dropped parts. Third, repeatability should be measured by comparing the final placement location over repeated cycles. Fourth, cycle time should be measured from the start of the pick command to completion of the return-to-home sequence. Fifth, pneumatic stability should be checked by monitoring pressure during repeated operation.

Table 3. Experimental Testing Parameters and Acceptance Targets

Test	Measurement	Suggested acceptance target
Pick success	Successful grasps / total cycles	≥98% for controlled workpieces
Placement repeatability	Maximum position deviation	≤±3 mm
Cycle time	Pick-to-home duration	≤5 s
Pressure stability	Pressure variation during cycle	Within regulator setting ±10%
Payload	Maximum safe test mass	≥2 kg design case

Engineering interpretation

The calculated force margin indicates that a 32 mm cylinder at 0.6 MPa can provide considerably

more force than the minimum static force associated with a 2 kg payload. This does not mean that the arm can safely lift an arbitrarily larger load, because link bending, joint bearings,

cylinder buckling, frame stiffness, and dynamic loads can become limiting factors. The gripper is similarly critical: adequate cylinder force must be converted into reliable jaw force through the gripper mechanism. The literature indicates that industrial gripper performance depends on force, stroke, mass, and geometry, which supports evaluating these parameters together rather than selecting the gripper solely by nominal payload (Birglen & Schlicht, 2018).

Discussion

The proposed methodology combines conventional pneumatic hardware with simple digital sequencing. Its principal advantage is engineering simplicity. Pneumatic cylinders and valves can provide rapid linear actuation, while a PLC or microcontroller can coordinate the pick-and-place cycle. This architecture is consistent with earlier pneumatic manipulation studies, including the pneumatic feeding gripper of Michalos et al. (2018) and the pneumatic robotic arm demonstrated by Ohta et al. (2018).

At the same time, pneumatic systems have limitations. Air compressibility can reduce positional stiffness compared with a servo-driven electric axis, and changes in pressure or flow can affect motion speed. Gripping force is also influenced by regulator setting, valve response, friction, and the workpiece surface. Kaizu et al. (2019) demonstrated that pneumatic logic can combine grasping and lifting functions, but industrial implementations still benefit from sensors and interlocks when reliability is important. For higher-speed production, the arm can be upgraded with proportional valves, position sensors, a servo wrist, or vision-based object detection.

Another consideration is the relationship between cycle time and mechanical motion. A

shorter cycle generally requires higher actuator speed, but excessive speed can increase impact, vibration, and placement error. Therefore, flow-control valves and soft end stops should be tuned during commissioning. If the workpiece is fragile or has variable geometry, an adaptive gripper may be preferable to a fixed two-jaw design. The literature on robotic grippers shows a broad movement toward greater adaptability while retaining industrial robustness (Tai et al., 2016).

Conclusion

This paper presented a step-by-step methodology for designing and analysing a pneumatic pick-and-place robotic arm for industrial material handling. The proposed system uses double-acting pneumatic cylinders, a two-jaw pneumatic gripper, regulated compressed air, directional control valves, and PLC/microcontroller sequencing. For a representative 2 kg payload and 0.6 MPa operating pressure, a 32 mm cylinder provides an ideal force of approximately 483 N, while the estimated payload torque at 0.30 m reach is approximately 5.89 N·m. These calculations indicate that the selected actuator class is feasible for the stated design case, subject to structural and dynamic verification. The methodology provides a practical basis for fabrication and experimental validation. Future work should include CAD-based stress analysis, finite-element verification of the links and base, experimental cycle-time testing, repeatability measurement, pressure monitoring, and optimization of the gripper for different workpiece shapes. A vision system and conveyor tracking can subsequently be incorporated for more flexible industrial sorting and material-flow applications.

Key design steps at a glance

Table 4. Sequential Methodology for Design, Development, and Validation

Step	Activity	Output
1	Define payload, reach and cycle	Design requirements
2	Select arm geometry	Link dimensions and workspace
3	Size cylinders	Force and torque margin
4	Select gripper	Reliable grasping
5	Design pneumatic circuit	FRL, valves and flow control
6	Implement control logic	Automatic pick-place sequence
7	Validate prototype	Payload, repeatability, cycle time

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