Design and Implementation of a Portable Electropneumatic Bottle Filling and Capping Machine with Relay-Based Control

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***Abstract*-** This paper presents the design, fabrication and testing of a compact, castor-mounted electropneumatic machine that feeds, fills and caps bottles automatically. Developed as a mechatronics capstone project for small-scale production and laboratory teaching, the machine carries bottles on a rotary indexing table, advanced by a ratchet-and-pawl mechanism, through pushing, filling and capping stations. Four double-acting pneumatic cylinders, each driven by a single-solenoid 5/2-way valve, perform the motions. The complete sequence is implemented in hard-wired 24 V DC relay logic built from 14 control relays, an on-delay timer that sets the fill period and a preset counter that groups bottles into sets of three, with end-position and bottle-presence sensors interlocking every station. The mechanism was modeled in SolidWorks and validated with a full-scale CNC-cut MDF mock-up before the final machine was built. The paper documents the pneumatic circuit and every relay rung, summarizes the set, seal-in and release conditions of each relay, and derives a simple timing model that links fill volume and throughput to the timer preset and the cylinder stroke times. The prototype performs a continuous fill-and-cap cycle without operator intervention, showing that low-cost relay logic can reproduce the sequencing and interlocking of a PLC-controlled packaging line while keeping every signal visible for teaching and fault-finding.

***Index Terms*-** Bottle filling and capping, electropneumatics, mechatronics education, relay ladder logic, rotary indexing table

I. Introduction

Automated filling and capping is a core operation in the beverage, food, pharmaceutical and personal-care industries, where every container must receive the correct quantity of product and be sealed consistently. Industrial lines achieve this with servo-driven rotary fillers supervised by programmable logic controllers (PLCs) [1], [2], equipment that is often more costly and complex than a small producer or a teaching laboratory needs. Pneumatic actuation is a cheaper alternative: cylinders and solenoid valves are rugged, easy to maintain and well suited to the short, repetitive strokes of a bottling cycle [3], [4].

Relay logic is the historical predecessor of PLC programming. A circuit built from relays, timers and counters expresses the same ideas of sequencing, latching (seal-in) and interlocking that a PLC ladder program does [2], [5], but every contact is physically visible and can be probed with a meter. A relay-controlled machine is therefore a good vehicle for learning how automated sequences are constructed and debugged before the same logic is moved into software.

This paper describes a portable electropneumatic bottle filling and capping machine that combines these ideas. The objectives were to:

1) design a compact, castor-mounted machine that feeds, fills, caps and releases bottles automatically;
2) model the mechanism in SolidWorks and validate its fit and layout with a low-cost mock-up before final fabrication;
3) implement the full control sequence with 24 V DC relays, a timer and a counter, using sensor feedback to interlock every station; and
4) build, wire and test the prototype, and refine the sequence for synchronized, repeatable operation.

The contributions of the paper are a complete, reproducible description of the relay control circuit, down to the set, seal-in and release condition of every relay; a two-way interlock between the indexing table and the working stations that is achieved without a PLC; and an analytical timing model that identifies the parameters governing fill volume and throughput. Section II reviews related work and Section III gives an overview of the machine and its operating cycle. Sections IV to VI describe the mechanical, pneumatic and electrical design. Section VII reports testing and discusses the results and limitations, and Section VIII concludes the paper.

II. Related Work

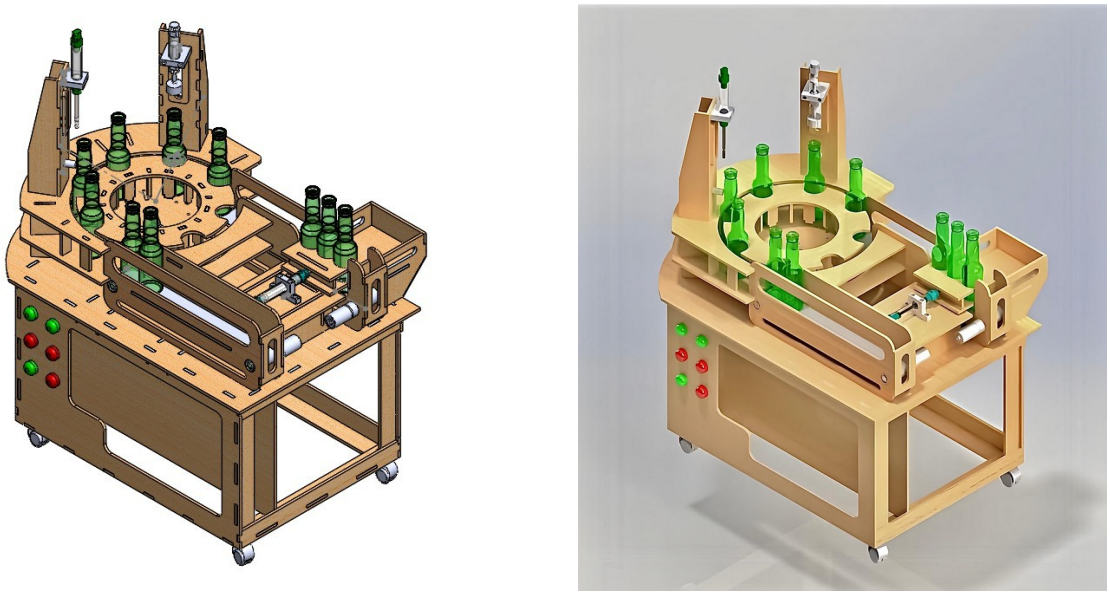
Automatic bottle filling has been a popular subject of PLC-based design work for more than two decades. Shaukat [6] presented an early PLC-controlled liquid filling process, and later studies have added closed-loop PLC control of a filling-capping system verified in ladder-logic simulation [7] and conveyor-based machines that fill through a pump and solenoid valve and tighten the cap with a motor-driven head [8]. Tupsakri et al. [9] used a stepper-driven rotating mechanism with servo-actuated pushers under Arduino

control, a layout close to the rotary arrangement adopted here. In an educational setting, Šitum et al. [10] described pneumatically actuated mechatronic teaching models, including a compact filling and capping conveyor with a pneumatic capping cylinder controlled by a compact PLC.

Nearly all of these systems rely on a PLC or a microcontroller, so the control logic is held in software. Reports of machines whose complete sequence is realized in hard-wired relay logic, and documented down to the individual rung, are much less common. The present work addresses that gap with a rotary, fully pneumatic machine whose control circuit can be read, wired and probed directly, and which can later be migrated to a PLC rung for rung.

III. System Overview and Operating Principle

The machine is a self-contained unit mounted on castors so that it can be moved between laboratories (Fig. 1). A rotary indexing table sits on top of a closed frame. The filling and capping stations stand on columns above the table, a feed tray with a pushing cylinder is located on the right-hand side, and the electrical panel and operator controls occupy the lower front of the frame. Bottles enter from the feed tray, are pushed onto the table, indexed from station to station, filled, capped and finally released.



(a) (b)

Fig. 1. SolidWorks model of the machine: (a) assembly model, (b) rendered view.

One machine cycle consists of four pneumatic steps, push, index, fill and cap, which are summarized in Fig. 2 and Table I. Each step starts only when the sensors confirm that the previous one is complete, so the stations cannot work against one another.

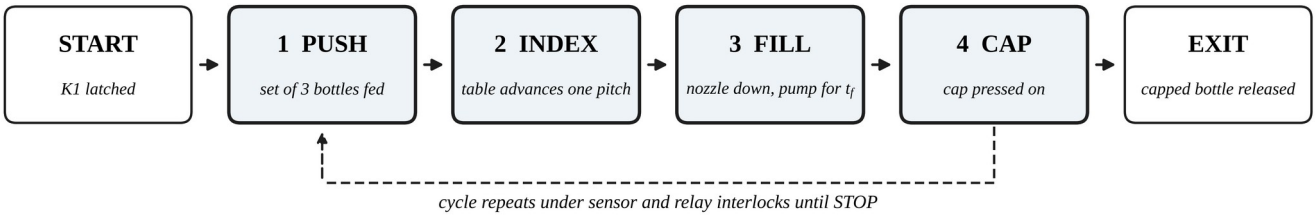


Fig. 2. Operating sequence of the machine.

TABLE I
Sequence of Operation

Step	Station	Action	Completion signal
1 Push	Feed tray	After the counter has registered a set of three bottles, the pushing cylinder feeds them onto the rotary table and returns.	1P2 (counter reset)
2 Index	Rotary table	The ratchet cylinder extends and returns, advancing the table by one pitch through the ratchet-and-pawl mechanism.	1R2, then 1R1
3 Fill	Filling station	The filler cylinder lowers the nozzle, the pump runs for the TIMER1 preset, and the nozzle retracts.	1F2, TIMER1, 1F1
4 Cap	Capping station	The capping cylinder presses the cap onto the bottle and returns.	1C2, then 1C1

IV. Mechanical Design and Fabrication

A. CAD Modeling in SolidWorks

The whole machine was modeled in SolidWorks before any part was cut, so that clearances, cylinder strokes and station positions could be checked on screen. The model includes the rotary indexing table with its bottle pockets, the actuator brackets and station columns, the feed tray and pusher guide, the operator panel layout and the castor-mounted frame, whose panels are joined with slot-and-tab connections (Fig. 1). Slot-and-tab joints let the flat panels locate one another during assembly, which suits CNC-cut sheet material.

B. Rotary Indexing Mechanism

Bottles are carried in pockets around the rotary table and are guided by a curved fence as the table turns (Fig. 1). The table is advanced by a ratchet-and-pawl mechanism driven by the ratchet cylinder: during one stroke the pawl engages a tooth and turns the table by one pitch, and during the other it slides back over the next tooth while the table remains at rest. Each index therefore requires one complete extend-and-return stroke, which is confirmed by the end-position sensors 1R2 and 1R1. Dial-indexing arrangements of this kind are widely used in automated assembly and packaging because every station works on a different part during the same dwell [1].

C. Mock-up and Fabrication

CNC-cut MDF parts were first assembled into a full-scale mock-up to prove the fit and layout of the design (Fig. 3a, 3b). Once the geometry had been verified, the final machine was fabricated and its pneumatic and electrical systems were assembled to match the CAD model, with fabricated mounts holding the cylinders, valves and sensors in alignment (Fig. 3c and Fig. 4). Proving the geometry in inexpensive material first allowed mounting and clearance problems to be found before the final parts were made.



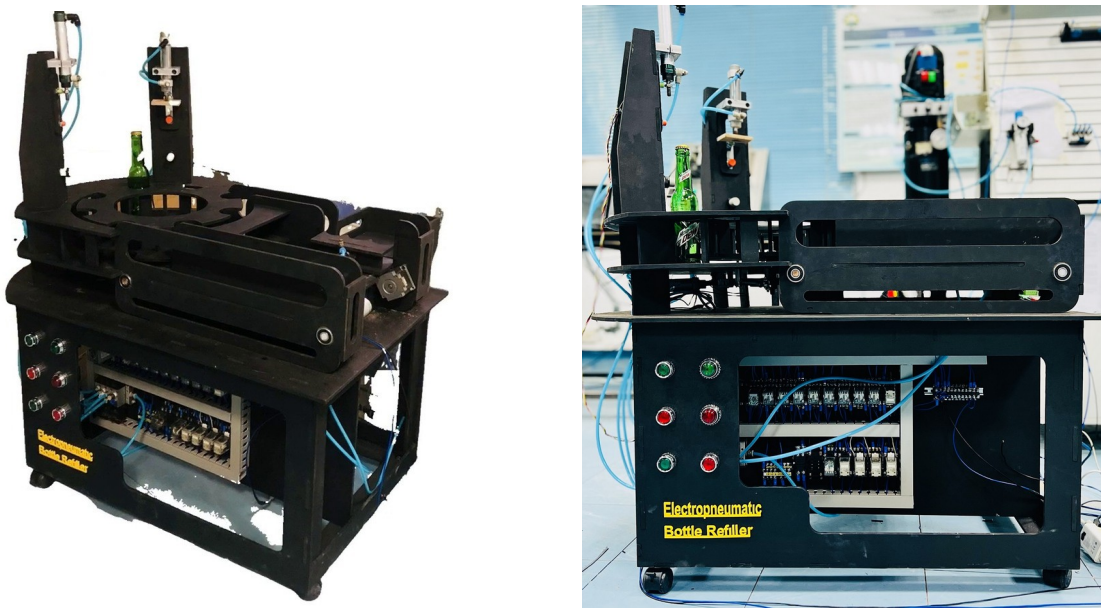
(a) (b) (c)

Fig. 3. From mock-up to machine: (a), (b) CNC-cut MDF mock-up used to prove fit and layout; (c) fabricated machine showing the rotary table, station columns and feed mechanism.

V. Pneumatic System

Four double-acting cylinders perform the machine's motions: pushing, indexing (ratchet), filling and capping (Table II). Each cylinder is driven by a single-solenoid, spring-return 5/2-way directional control valve, and a one-way flow-control valve sets the piston speed. The circuit is drawn with graphical symbols according to ISO 1219-1 [11] in Fig. 5. End-position sensors on the cylinders (1F1/1F2, 1C1/1C2, 1R1/1R2 and 1P2) report completed strokes to the relay circuit. Because strokes are confirmed by sensors rather than by fixed delays, each step starts as soon as the previous one has finished, and only the filling period is time-based.

A useful property of single-solenoid, spring-return valves is that a de-energized valve always returns its cylinder to the home position. Since every rung of the control circuit is fed through the master relay K1 (Section VI-B), pressing STOP de-energizes all four solenoids and the pump, and every cylinder retracts.



(a) (b)

Fig. 4. Assembled prototype: (a) isometric view, (b) front view with the operator controls and the relay panel.

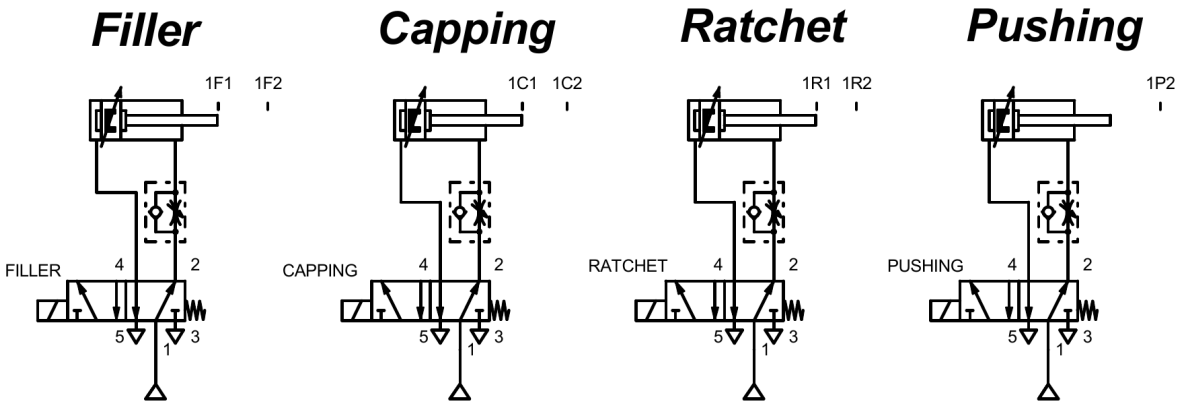


Fig. 5. Pneumatic circuit (ISO 1219-1 symbols): double-acting cylinders with single-solenoid 5/2-way valves and one-way flow-control valves for the filler, capping, ratchet and pushing actions.

TABLE II
ACTUATORS, VALVES AND POSITION SENSORS

Actuator	Function	Control element	Position sensors
Pushing cylinder	Feeds bottles from the tray onto the rotary table	5/2 valve, solenoid PUSHING	1P2
Ratchet cylinder	Indexes the table by one pitch through the ratchet-and-pawl mechanism	5/2 valve, solenoid RATCHET	1R1, 1R2
Filler cylinder	Lowers and raises the filling nozzle	5/2 valve, solenoid FILLER	1F1, 1F2
Capping cylinder	Presses the cap onto the bottle	5/2 valve, solenoid CAPPING	1C1, 1C2
Pump	Dispenses the liquid while the nozzle is lowered	Relay PUMP	Timer-controlled (TIMER1)

VI. ELECTRICAL AND CONTROL SYSTEM DESIGN

A. Control Architecture

The machine is controlled by 24 V DC relay logic, which is structurally a ladder diagram: contacts form the rungs, and relay coils or valve solenoids are the outputs [2], [5]. The rungs are grouped by function into master control, bottle counting and pushing, indexing, filling and capping. In total the circuit uses 14 control relays, one on-delay timer (TIMER1), one preset counter, three bottle sensors (COUNTER_SENSOR, F_B_D and P_B_D), seven cylinder end-position sensors and four solenoid valves (Table III). Signal names follow the circuit diagrams; the suffix _R denotes the relay energized by the sensor or command of the same name.

B. Master Control Relay

A master relay K1 is latched by the START push button through its own contact and released by the STOP push button (Fig. 6, left). Its contacts supply all other rungs, so no output can be energized until START has been pressed and every output drops out when STOP is pressed. Illuminated push buttons and pilot lamps on the front panel form the operator interface (Fig. 4b).

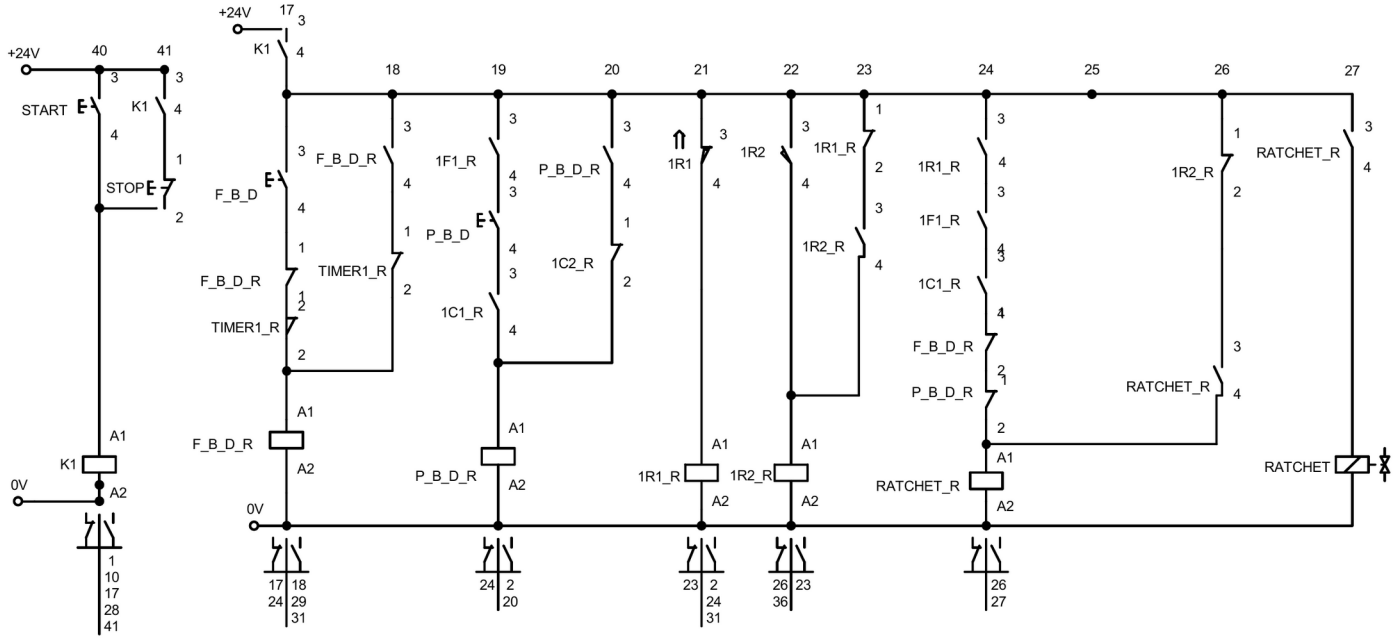
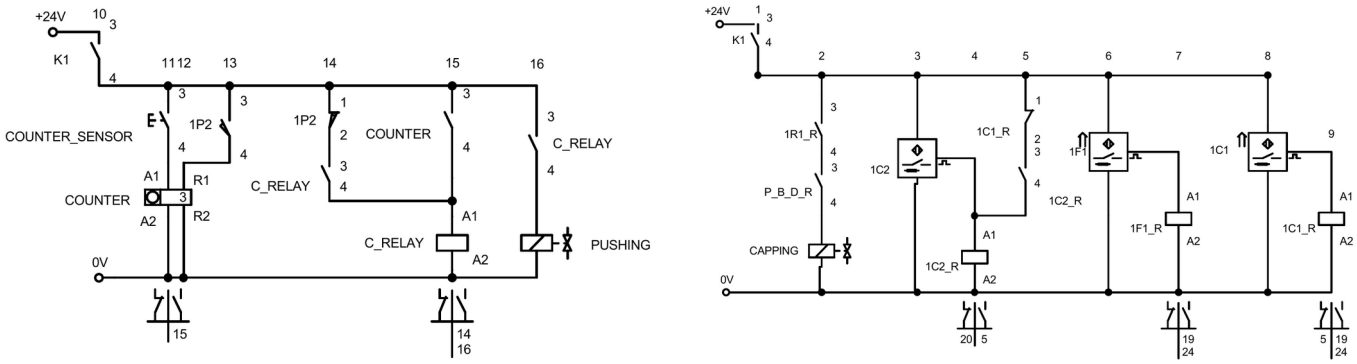


Fig. 6. Relay circuit for the START/STOP master relay K1 (left) and for the ratchet-and-pawl indexing actuator, including the bottle-detection and ratchet end-position relays.

C. Bottle Counting and Pushing

The counter circuit (Fig. 7a) counts pulses from COUNTER_SENSOR. When the preset of three bottles is reached, the counter contact energizes C_RELAY, which seals itself in through its own contact and the normally closed contact of the pusher end-position sensor 1P2, and energizes the PUSHING valve. When the pusher reaches its extended position, 1P2 opens the seal-in path, so C_RELAY drops out and the cylinder returns; at the same time the normally open contact of 1P2 resets the counter for the next set.



(a) (b)

Fig. 7. Relay circuits for (a) counting a set of three bottles and operating the pusher, (b) controlling the capping cylinder, together with the filler and capper home-position relays.

D. Indexing with the Ratchet-and-Pawl Actuator

The RATCHET valve is energized through the command relay RATCHET_R (Fig. 6). RATCHET_R can be set only when the ratchet cylinder is home (1R1_R), the filler and the capper are both retracted (1F1_R and 1C1_R), and no fill or cap request is pending (F_B_D_R and P_B_D_R released). Once set, it seals in through its own contact and the normally closed contact of 1R2_R. When the cylinder reaches its extended end position, 1R2_R opens this path, the valve is de-energized and the cylinder returns; 1R2_R itself stays latched until 1R1_R confirms that the cylinder is home again.

Conversely, the filler and capping valves both require 1R1_R (Sections VI-E and VI-F), so neither station can extend while the ratchet is away from home. Together these conditions form a two-way interlock: the table cannot index while a tool is lowered, and no tool can be lowered while the table is indexing.

E. Filling Process

The bottle-detection sensor F_B_D sets relay F_B_D_R, which then holds itself until the fill is complete (Fig. 6). F_B_D_R energizes the filler cycle relay FILLER_R, and the FILLER valve lowers the nozzle when F_B_D_R, FILLER_R and 1R1_R are all closed, that is, when a bottle is present and the table is at rest (Fig. 8). At the lower end position, sensor 1F2 sets relay 1F2_R, which starts the on-delay timer TIMER1 and switches on the PUMP relay. When TIMER1 times out, its output relay TIMER1_R stops the pump and releases F_B_D_R, while the timed break contacts of TIMER1 open the seal-in paths of FILLER_R and 1F2_R, so the nozzle retracts.

TIMER1 then remains energized through its own contact until 1R2_R signals the next index stroke. Until that moment TIMER1_R blocks F_B_D_R, so the same bottle cannot be filled twice. The delivered volume is set by the timer preset and the pump flow rate and can be adjusted at the timer (Section VII-C).

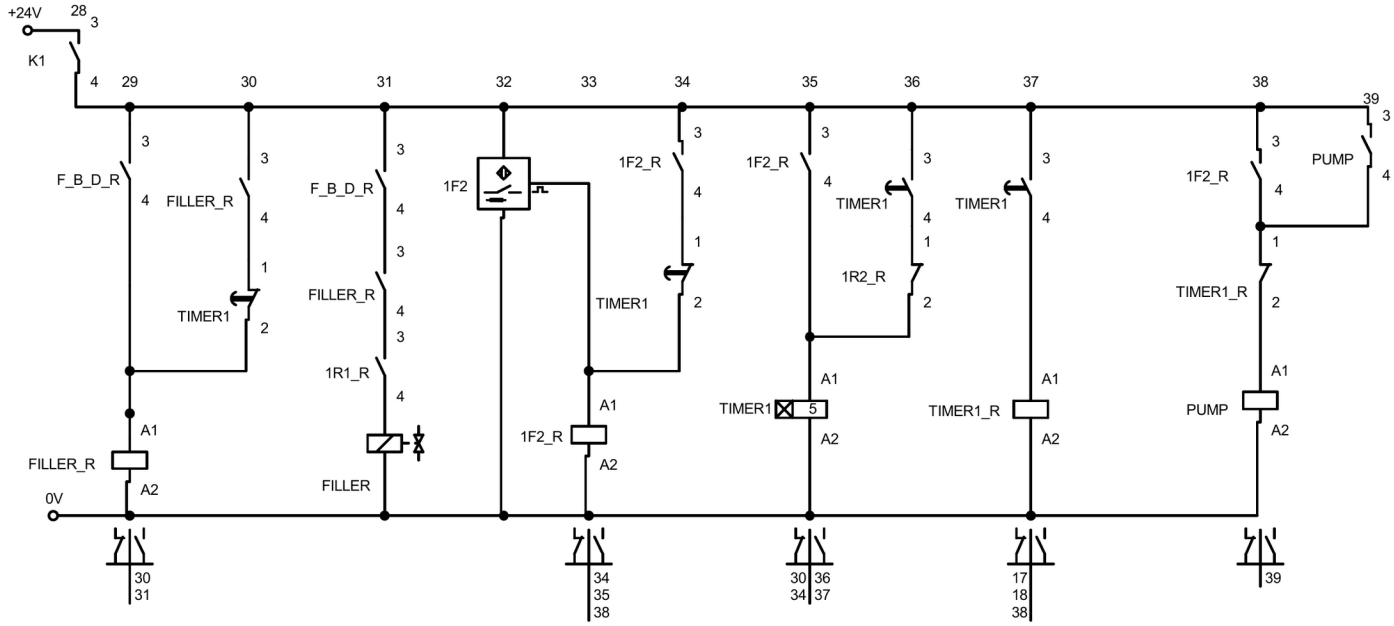


Fig. 8. Relay circuit for the filling process: filler cycle relay, FILLER valve, nozzle end-position relay, on-delay timer TIMER1 and pump relay.

F. Capping Process

A bottle at the capping position is registered by P_B_D, which sets relay P_B_D_R provided that the filler and the capper are both retracted (1F1_R and 1C1_R) (Fig. 6). The CAPPING valve is energized when P_B_D_R is set and the ratchet cylinder is home (1R1_R) (Fig. 7b). The capping cylinder extends until sensor 1C2 is reached; relay 1C2_R then opens the seal-in path of P_B_D_R, the valve is de-energized and the cylinder returns. 1C2_R remains latched until sensor 1C1, through relay 1C1_R, confirms that the capper is home, and this confirmation is one of the conditions for the next index.

TABLE III
MAIN RELAYS AND SIGNALS IN THE CONTROL CIRCUIT

Signal	Type	Function in the circuit
K1	Relay	Master control relay; latched by START, released by STOP; supplies all rungs.
COUNTER_SENSOR, COUNTER, C_RELAY	Sensor, counter, relay	Count incoming bottles, form a set of three and trigger the pushing cylinder.
F_B_D, P_B_D (F_B_D_R, P_B_D_R)	Sensors (relays)	Bottle presence at the filling and capping positions; the relays hold a pending fill or cap request.
FILLER_R	Relay	Filler cycle relay that enables the FILLER valve.
1F1_R, 1F2_R	Relays	Filler cylinder home and lowered end positions.
TIMER1, TIMER1_R	On-delay timer, relay	Sets the fill period; the output relay ends the fill.
PUMP	Relay	Switches the dispensing pump while the nozzle is lowered.
1C1_R, 1C2_R	Relays	Capping cylinder home and extended end positions.
1R1_R, 1R2_R, RATCHET_R	Relays	Ratchet cylinder home and extended end positions; indexing command.

G. Interlock Summary

Table IV lists, for every relay and valve, the condition that sets it, the seal-in path that holds it and the signal that releases it. The table is a compact textual form of the ladder diagram and is the starting point for migrating the machine to a PLC: each row maps to one rung with a set branch, a seal-in branch and a break contact [5], [12].

TABLE IV
SET, SEAL-IN AND RELEASE CONDITIONS OF THE CONTROL CIRCUIT

Output	Set condition (series contacts)	Seal-in path	Released by
K1	START	Own contact	STOP (NC)
C_RELAY	COUNTER preset (3 bottles) reached	Own contact via NC 1P2	1P2; also resets COUNTER
PUSHING valve	C_RELAY	—	C_RELAY released
F_B_D_R	F_B_D	Own contact	TIMER1_R (NC)
FILLER_R	F_B_D_R	Own contact via timed NC of TIMER1	TIMER1 timeout, with F_B_D_R released
FILLER valve	F_B_D_R, FILLER_R, 1R1_R	—	Any of these released
1F2_R	1F2	Own contact via timed NC of TIMER1	TIMER1 timeout, with 1F2 released
TIMER1	1F2_R	Own timed contact via NC 1R2_R	1R2_R (next index stroke)
TIMER1_R	Timed NO contact of TIMER1	—	TIMER1 reset
PUMP	1F2_R	Own contact	TIMER1_R (NC)
P_B_D_R	P_B_D, 1F1_R, 1C1_R	Own contact via NC 1C2_R	1C2_R
CAPPING valve	P_B_D_R, 1R1_R	—	Either released
1C2_R	1C2	Own contact via NC 1C1_R	1C1_R (capper home)
RATCHET_R	1R1_R, 1F1_R, 1C1_R and NC F_B_D_R, NC P_B_D_R	Own contact via NC 1R2_R	1R2_R
RATCHET valve	RATCHET_R	—	RATCHET_R released
1R2_R	1R2	Own contact via NC 1R1_R	1R1_R (ratchet home)

NC = normally closed contact. Relays 1F1_R, 1C1_R and 1R1_R follow sensors 1F1, 1C1 and 1R1 directly. Every rung is supplied through a contact of K1.

H. Electrical Panel Integration

The relays, timer, terminal blocks and connectors are wired in an open panel behind an opening in the lower front of the frame, with the illuminated push buttons and pilot lamps on the front face as the operator interface (Fig. 4b and Fig. 9). Keeping every relay visible makes fault tracing and classroom demonstration straightforward, because the state of each rung can be checked directly with a meter.



Fig. 9. Relay panel with the on-delay timer, control relays and valve manifold.

VII. TESTING, RESULTS AND DISCUSSION

A. Testing and Refinement

Testing proceeded in stages: first the individual cylinder strokes and sensor signals, then the relay circuit of each station, and finally the integrated sequence. Functional tests and troubleshooting were used to adjust the sensor positions, the timing and the sequence logic until the stations operated in a synchronized, repeatable manner with minimal errors.

B. Results

The final outcome is a fully functional electropneumatic machine that performs bottle entry, filling, capping and release autonomously in a continuous cycle (Fig. 4). Sensor-based interlocks prevent mis-sequenced motion, the fill period is tuned at a single timer, and pressing STOP returns every cylinder to its home position. The prototype is compact enough to be moved between laboratories on its castors and serves as a demonstrator for both electropneumatics and sequential control.

C. Timing Model

Quantitative throughput and fill-accuracy measurements were outside the scope of this prototype, but the control logic fixes the structure of the cycle and allows a simple model to be written. With a pump of volumetric flow rate Q_p and a TIMER1 preset t_f, the volume dispensed into each bottle is

$$V = Q_p \, t_f \tag{1}$$

The filling and capping stations work on different bottles during the same dwell of the table, and the table cannot index until both have returned home. Neglecting relay switching times, the dwell time is set by the slower station,

$$t_d = \max(t_{F,e} + t_f + t_{F,r},\ t_{C,e} + t_{C,r}) \tag{2}$$

where $t_{F,e}$, $t_{F,r}$, $t_{C,e}$ and $t_{C,r}$ are the extend and return stroke times of the filler and capping cylinders. Because the stations may move only when the ratchet cylinder is home, the index time t_i is the sum of the ratchet extend and return strokes. Assuming every pocket is occupied, so that one bottle is completed per index, the cycle time and the steady-state throughput in bottles per hour are

$$T_c = t_i + t_d, \qquad N = 3600 \,/\, T_c \tag{3}$$

Equations (1)–(3) separate the adjustable parameters of the machine: the timer preset sets the fill volume for a given pump, while the flow-control valves set the stroke times and hence the remaining part of the cycle. Throughput can therefore be raised either with a higher-flow pump, which shortens t_f for the same volume, or with faster cylinder strokes. Measuring these terms on the prototype is the natural next step.

D. Relay Logic Versus PLC Control

Table V compares the hard-wired implementation with a PLC-based alternative. For a four-actuator machine the relay solution is low in cost and completely transparent, which suits teaching and small, fixed sequences. Its drawbacks are those of all hard-wired logic: any change to the sequence requires rewiring, and the relay count and wiring effort grow with every added station [2].

TABLE V
RELAY LOGIC COMPARED WITH PLC CONTROL

Aspect	Hard-wired relay logic (this work)	PLC-based control
Changing the sequence	Rewiring of contacts and coils	Editing and downloading the program
Visibility of the logic	Every contact is physically visible and measurable	Logic is viewed through programming software or an HMI
Timers and counters	One physical device per function	Many software timers and counters without extra hardware
Adding stations	Relay count and wiring grow with every station	Mainly additional I/O points and rungs
Diagnostics	Meter and visual inspection	Online monitoring of status bits and fault logging
Teaching value	Shows the physical meaning of seal-in and interlock	Teaches the standard languages of IEC 61131-3 [12]

E. Limitations and Future Work

The fill volume is controlled in open loop by time, so its accuracy depends on the pump flow rate and the liquid properties. The prototype has no cap-presence check, and the STOP push button provides a normal stop rather than a dedicated emergency-stop function with guarding, which industrial use would require. Natural extensions include replacing the relay logic with a PLC programmed according to IEC 61131-3 [12] together with an HMI, adding a flow meter or load cell for closed-loop dosing, adding cap-presence sensing, and measuring the terms of (2) and (3) to characterize throughput and fill accuracy.

VIII. CONCLUSION

A portable electropneumatic bottle filling and capping machine was designed in SolidWorks, validated with an MDF mock-up, fabricated, wired and tested. Four sensor-monitored pneumatic cylinders and a 24 V DC relay circuit with 14 relays, a timer and a counter automate bottle entry, indexing, filling, capping and release in a continuous cycle. A two-way interlock ensures that the table never indexes while a tool is lowered and that no tool is lowered while the table moves, and spring-return valves supplied through a master relay return every cylinder home on STOP. The work shows that the sequencing and interlocking of a PLC-based packaging line can be reproduced with simple, visible relay logic, and it provides a compact, fully documented platform for teaching electropneumatics and industrial automation that can later be migrated to a PLC rung for rung.

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DATA AVAILABILITY

The SolidWorks models, the pneumatic and relay circuit diagrams and a video of the machine in operation are available from the corresponding author on reasonable request.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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