Bistable valves in safety-related applications. An example.

FESTO

Summary: Due to their bistable characteristics, bistable valves in certain applications present the user with tasks that seem to be difficult to solve. This application example is to show how a solution can be developed systematically taking the various operating states and operating transitions into account. Considering the various hazards in the various operating statuses of the machine appears a sensible approach to finding the solution. They require chronologically successive, different reactions of the safety circuit to implement the required protective measures.

Foreword

The publication of the article "Bistable Valves in Safety-Related Applications" in Technical Report TR-300002 was welcomed by industrial users and research institutes alike. With reference to such articles, users of our components and the operators of machines can clarify major open points relating to safety-related validation.

For a differentiated engineering presentation, we neglected to offer comprehensive, practically oriented application examples. Closing this gap with this supplementary example and fulfilling the wishes of many readers is the aim of this Technical Report TR-300003.

1 Bistable valves in standard circuits

Even in non-safety-related applications or standard circuits such as Figure 1, a major property of these valves must be observed. Once a movement of the drive is initiated, it cannot be stopped or reversed by deactivating the solenoid actuated pilot valve in the bistable valve. The solution method of reversing the bistable valve proves impossible or difficult to implement on closer consideration. This procedure also contravenes an important safety principle – assumption of a safe status on energy shut-off [1-3].

This describes the second main property of bistable valves: once a switching position is reached, it persists and additional energy supply[1] is required to leave it.

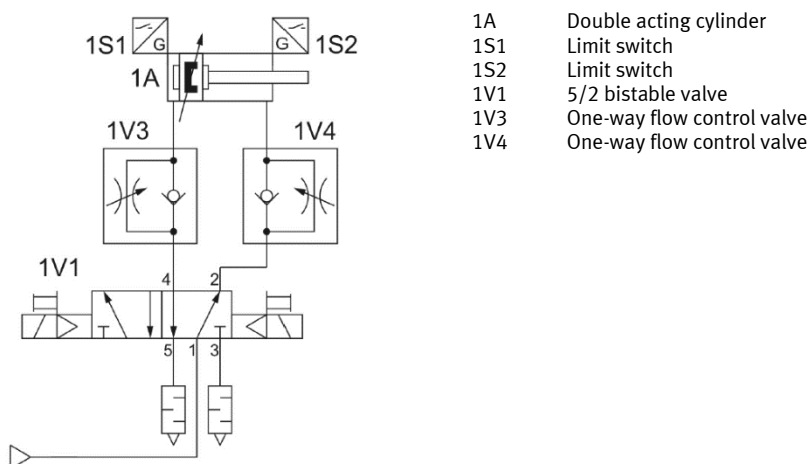|	
1A	Double acting cylinder
1S1	Limit switch
1S2	Limit switch
1V1	5/2 bistable valve
1V3	One-way flow control valve
1V4	One-way flow control valve

Figure 1: Standard circuit for a double-acting cylinder

2 Additional requirements

Daily practice shows that as project processing continues, and as a project passes through the individual departments of a company, the requirements for a system gradually become clear. This fact also explains the constantly changing problems in implementing technical solutions. The final demand, which is probably not received until the machine is accepted by the customer, often relates to operation with open guards. In addition to these permanent changes, the runtime-related delays and overlaps in decisions and status statements result in added difficulty.

A promising approach to mastering this problem is to consider the sequence of the individual operating states and modes of the machine. Based on the schematic representation in Figure 2, the sequence of the operating modes of the machine can be determined rapidly. Once this sequence is known, the sequence of hazards can also be determined rapidly. This is the first important step in determining the safety functions – they are nothing more than the answer to the hazards which occur.

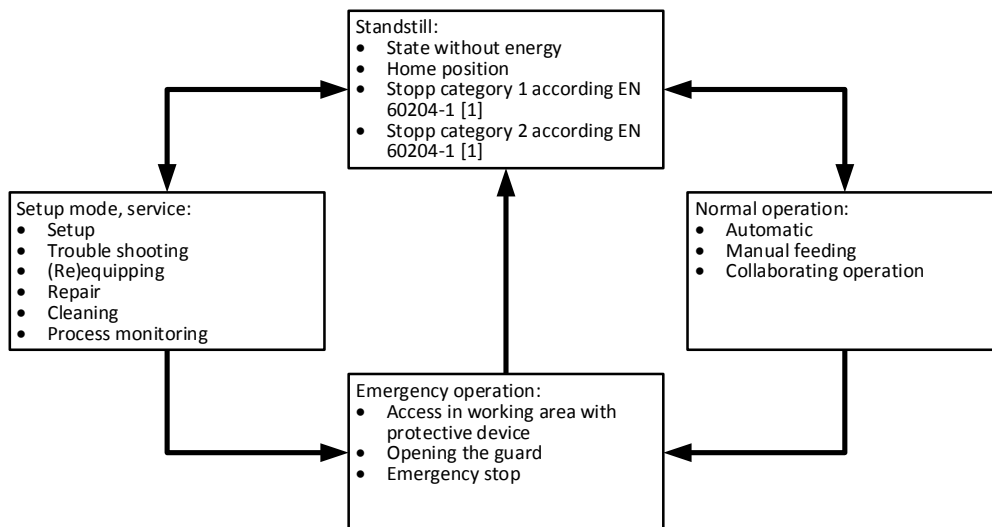[1] The scope of the statement refers to compliance with the permissible operating conditions.

Figure 2: Sequence of operating modes or operating statuses of a machine[2]

Regardless of the specific hazard situation in the system under consideration, pneumatics generally features hazards which recur again and again:

- Sudden movements on pressurisation of a pressure-free system,
- Sudden releases of energy (jumps on suddenly breaking free) in the event of movement blockages,
- Additional exposure during assembly and repair work[3],
- Due to unexpected start-up[4],
- Due to undefined states on pressure release and pressurisation.

3   Integration of the service unit

In general, every pneumatic system is fed from a service unit [4]. Therefore, it appears appropriate to incorporate this in the safety engineering considerations. Figure 3 shows the standard circuit introduced in section 1, supplemented with a service unit 0Z.
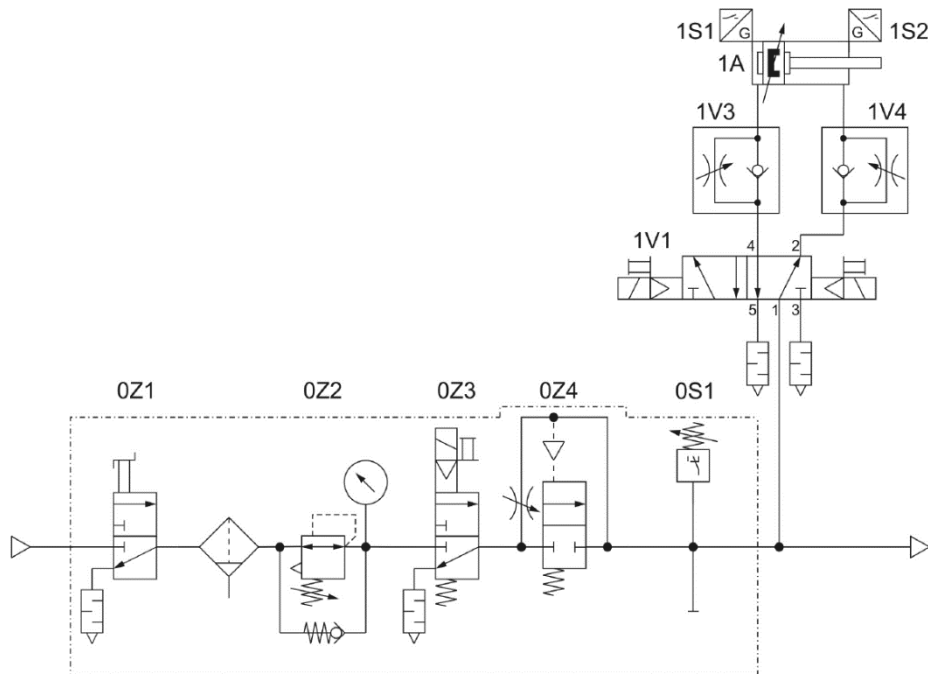
If pneumatic drives are actuated with the standard circuit in section 1, which remain in their assumed end position and are depressurised on blockages to movement, this can be implemented by incorporating valve 0Z3 of the service unit. If this solution is selected, you must check whether "depressurisation[5]" of all circuit components is permitted. The permitted switching cycle rates of the valves in the service unit are a further restriction.

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[2] The representation does not claim to be complete.
[3] This hazard is general and not restricted to pneumatics exclusively.
[4] This hazard is general and is also not restricted to pneumatics exclusively.
[5] For depressurisation, it must be considered that this measure can only be applied for drives without a dead point, lock position or clamp.

0Z1	On-off-valve	1A	Double acting cylinder
0Z2	Pressure regulator with manometer and filter	1S1	Limit switch
		1S2	Limit switch
0Z3	Valve for exhausting	1V1	5/2 bistable valve
0Z4	Soft start valve	1V3	One-way flow control valve
0S1	Pressure switch	1V4	One-way flow control valve

Figure 3: Circuit from figure 1 with service unit for depressurisation of the system

If the requirements of the Machinery Directive 2006/42/EC are implemented, malfunctions in the power supply must also be taken into consideration as part of project engineering. This automatically results in two other randomly forced status changes:

- Pressure-free system $\rightarrow$ Pressurised system (necessary for resuming production).
- Pressurised system $\rightarrow$ Pressure-free system (generally unintentional and not influenceable).

Hazards when pressurising the system (sudden movements) are prevented by valve 0Z4 for gradual pressure build-up. Due to the fact that depressurised drives have no defined forces, these drives can be made to take up any position by the forces which act on them[6]:

- Gravitational force,
- Process forces,
- Restoring forces of shock absorbers,
- Manual manipulation for clearing, cleaning, etc.

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[6] This statement refers to drives which are not subject to special blocking measures (brakes/clamps, toggle levers, etc.).

It is also often forgotten that changing drive forces can occur when depressurising a drive. This behaviour is due to the different volumes and flow resistances at both connections.

When pressurising the pneumatic system or switching on the compressed air supply, other hazards can occur due to failure to note technical conditions. If pilot-actuated valves are to be switched to a specific switching position before the pressure increases (to move the drives deliberately in a direction), using the circuit in figure 3 could still result in hazardous movements. This is due to the minimum switching pressure in pilot-actuated valves. They do not switch from the normal position to the switched position, or change their switching position, until a specific pressure is reached. In such cases, the function of the "gradual pressurisation" protective measure is at least partially cancelled out. Modifying the circuit according to figure 4 is a possible solution.

Observe the characteristics of 0Z4 to implement the depressurisation function. It is returned to the normal position at a specific pressure, just as the valve switches to the switched position from a specific switching pressure. To do this, the residual volume remaining in the system must be exhausted via the flow control valve in 0Z4. The pressure-time diagram in Figure 5 shows the resulting delayed pressure decrease (continuous line) and the exhaust time t_E of the pneumatic system.

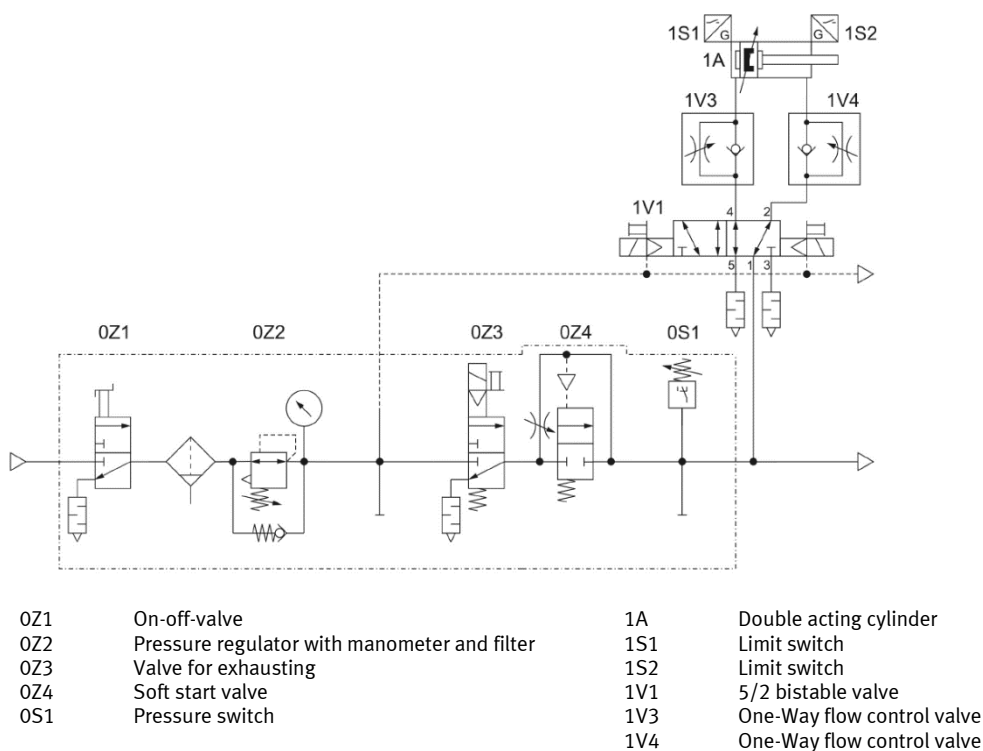| 0Z1	On-off-valve	1A	Double acting cylinder
0Z2	Pressure regulator with manometer and filter	1S1	Limit switch
0Z3	Valve for exhausting	1S2	Limit switch
0Z4	Soft start valve	1V1	5/2 bistable valve
0S1	Pressure switch	1V3	One-Way flow control valve
		1V4	One-Way flow control valve

Figure 4 Standard circuit with service unit for depressurisation of the system with the additional function of switching the power valves to any position
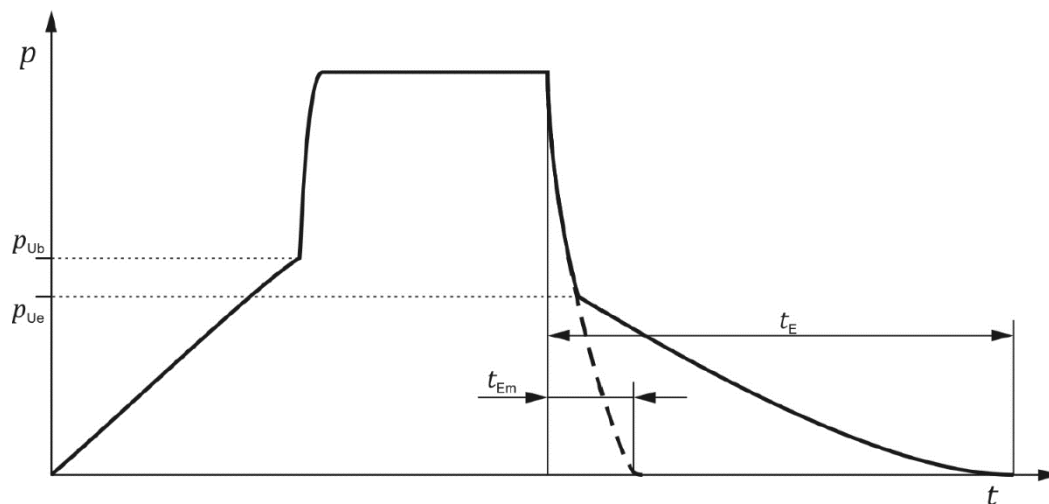
p_{Ub} = Switching pressure during pressurisation
p_{Ue} = Switching pressure during exhausting
t_E = Exhaust time of system
t_{Em} = Exhaust time of system with modification in service unit according to figure 6

Figure 5 Pressure curve in the system if using a valve for gradual pressure build-up

The challenge of a long exhaust time t_E can be solved by modifying the service unit slightly as per Figure 6. Valve 0Z4 is supplemented with check valve 0ZS. This "bypass" to avoid the flow control valve on depressurisation reduces the exhaust time t_{Em} considerably and speeds up pressure reduction (dashed line).
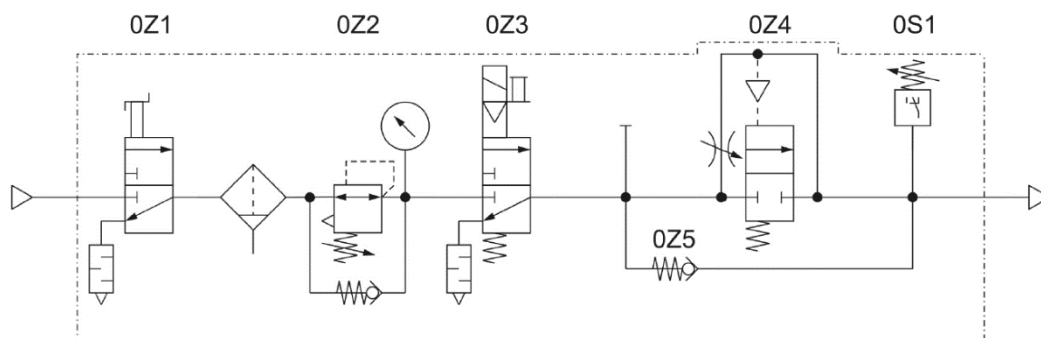
0Z1	On-off-valve	0Z4	Soft start valve
0Z2	Pressure regulator with manometer and filter	0Z5	Check valve with spring
0Z3	Valve for exhausting	0S1	Pressure switch

Figure 6: Modified service unit for reducing the exhaust time

If the service unit is incorporated in the safety concept, it makes sense to think about error detection measures (regardless of the categories to be implemented for the individual control circuit).

Pressure switches (0S1, Figure 6) are often used to detect pending operating pressure. This one switch is not sufficient for more advanced error detection. However, if this switch is combined with another pressure switch (0S2, Figure 7) to evaluate the lower pressure range (signal change at 0.2 to 0.3 bar), far more information can be gained by evaluating the sequence of the switching signals of both pressure switches:

- Feedback on the proper function of both pressure switches,
- Feedback on the maintenance of the switching points set,
- Feedback on correct return of 0Z4 to the normal position (evaluation of the signal change at 0S2 relative to 0S1),
- Detection of excessive operating pressure settings (above the permitted operating pressure).
- Detection when a harmless pressure level is reached,
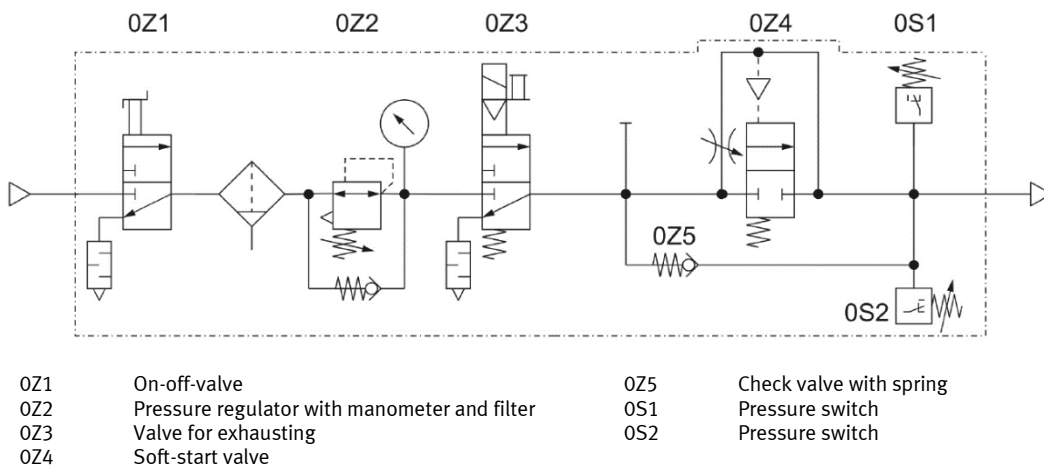- Feedback on the status of the silencer on 0Z3.

0Z1	On-off-valve	0Z5	Check valve with spring
0Z2	Pressure regulator with manometer and filter	0S1	Pressure switch
0Z3	Valve for exhausting	0S2	Pressure switch
0Z4	Soft-start valve		

Figure 7: Service unit with additional pressure switch for detecting the lower pressure range

4 Prevention of unexpected start-up in category 3

Prevention of unexpected start-up [5; 6] is relatively easy to implement for pilot-actuated valves. As the pilot air is switched separately for these valves, a second control channel can be created relatively easily for a planned category 3 [3] architecture. However, pneumatic switching in figure 8 has the disadvantage that valve 1V2 is logically directly assigned to valve 1V1 and cannot be used for other functions. If the circuit is changed so that the pilot air switching valve is permanently supplied with compressed air, additional functions can be used for other statuses and status transitions (figure 9).

For example, the restriction of not switching the valves before pressurising the system described under Point 3 no longer applies. As a result, all power valves (1V1 and other valves) can be moved to a specific switching position before valve 0Z3 is actuated.
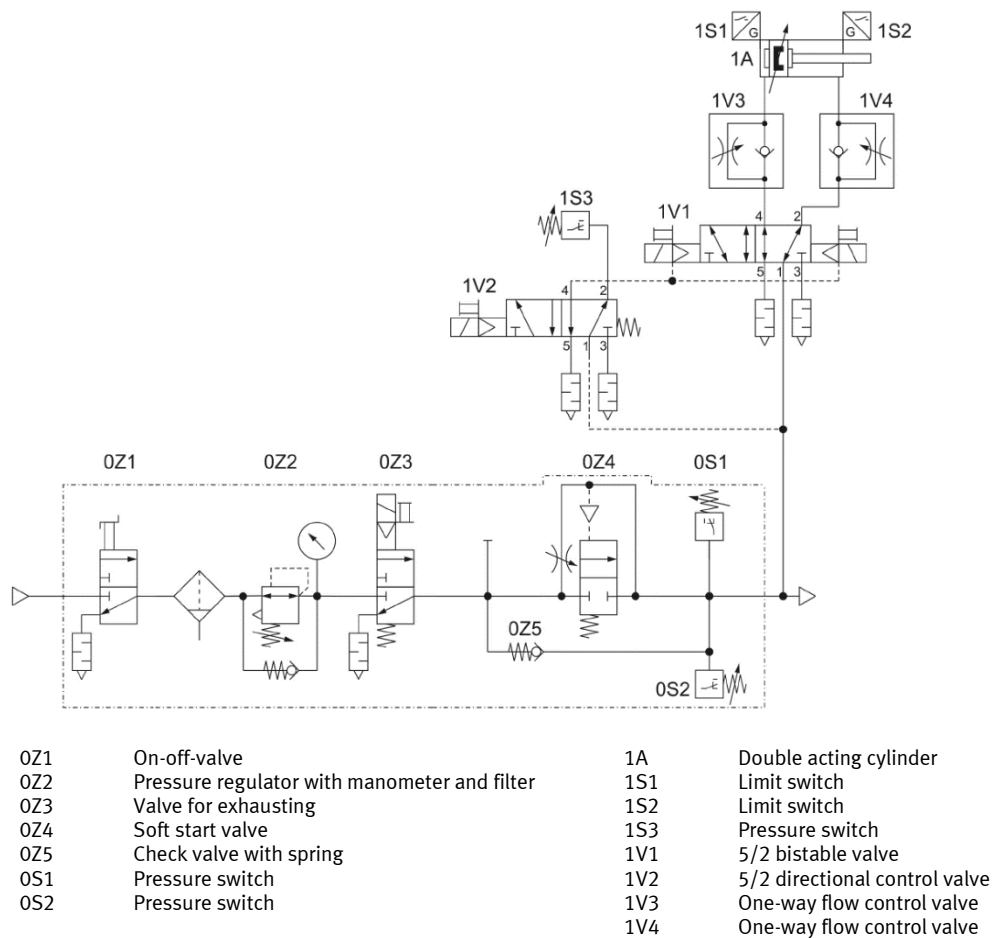
Figure 8: Structure of a two-channel control chain for protection against unexpected start-up

0Z1	On-off-valve	1A	Double acting cylinder
0Z2	Pressure regulator with manometer and filter	1S1	Limit switch
0Z3	Valve for exhausting	1S2	Limit switch
0Z4	Soft start valve	1S3	Pressure switch
0Z5	Check valve with spring	1V1	5/2 bistable valve
0S1	Pressure switch	1V2	5/2 directional control valve
0S2	Pressure switch	1V3	One-way flow control valve
		1V4	One-way flow control valve

If pressure maintenance measures (clamping force backup, position security, etc.) are required, the solution in figure 9 can no longer be used. A pressure maintenance function always conflicts with a pressure release function. The only way to solve[7] this conflict (excluding fundamental changes in the mechanical system) is to implement status switching in the circuit.

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[7] The solution is based on the assumption that compressed air is provided for the required period.
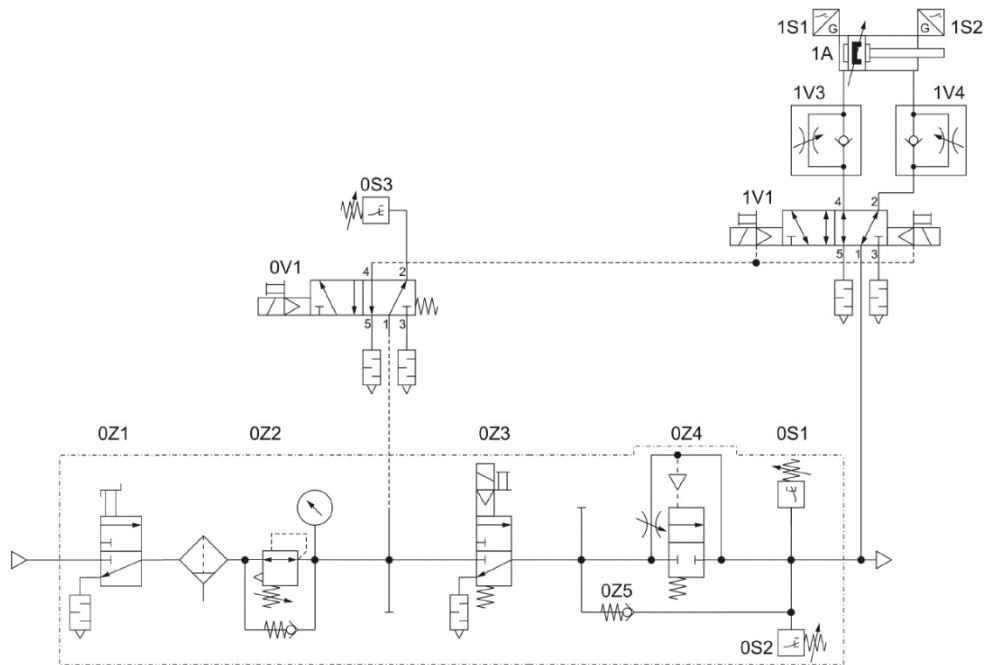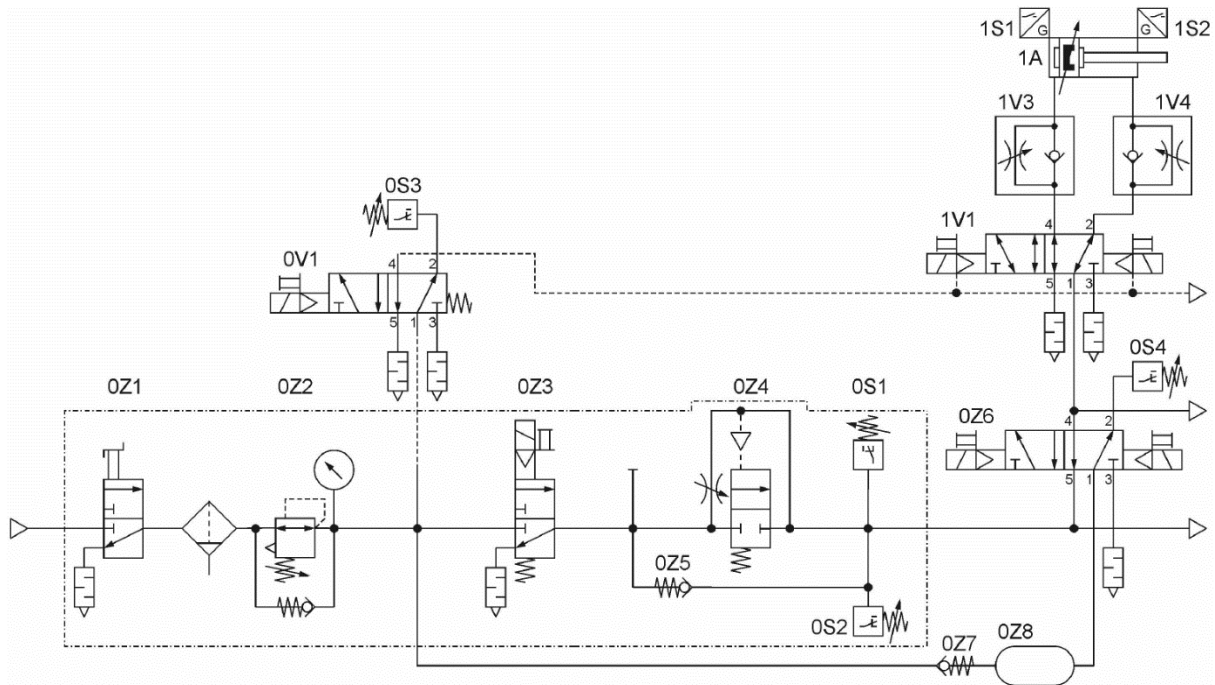
0Z1	On/off valve	0V1	5/2-way valve
0Z2	Pressure regulator with display and filter	1A	Double-acting cylinder
0Z3	Exhaust valve	1S1	Proximity sensor
0Z4	Soft-start valve	1S2	Proximity sensor
0Z5	Check valve with spring	1V1	5/2-way bistable valve
0S1	Pressure switch	1V3	One-way flow control valve
0S2	Pressure switch	1V4	One-way flow control valve
0S3	Pressure switch		

Figure 9: Structure of a two-channel control chain for protection against unexpected start-up with a permanently pressurised pilot air switching valve

This enables the circuit to act differently when the component safety function(s) are requested (figure 10). When the drive reaches its end position, the drive is still supplied with compressed air by switching 0Z6, even when the system is depressurised. The level of the "Safe compressed air supply" function determines the measures upstream of 0Z6 to prevent accidental status changes.

0Z1	On/off valve	0S3	Pressure switch
0Z2	Pressure regulator with display and filter	0S4	Pressure switch
0Z3	Exhaust valve	1A	Double-acting cylinder
0Z4	Soft-start valve	1S1	Proximity sensor
0Z5	Check valve with spring	1S2	Proximity sensor
0Z6	5/2-way bistable valve	1V1	5/2-way bistable valve
0Z7	Check valve with spring	1V3	One-way flow control valve
0Z8	Air reservoir	1V4	One-way flow control valve
0S1	Pressure switch		
0S2	Pressure switch		

Figure 10: Control chain with status switching

5 Status-dependent reactions

If a control chain is to respond differently when the safety function is requested for a status transition from A to B as it would for a status transition from B to A, additional control engineering measures[8] are necessary. The only possible solution is status switching of the control chain. Figure 11 shows an example for actuating a clamping device[9]:

- During the closing movement, the clamping device is to open when the "Protection against hazardous movements" safety function is requested (e.g. when the light curtain is penetrated),
- The clamping device is to remain closed if the safety function is requested when it is already closed.

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[8] The option of making fundamental changes to the mechanical system is not considered here.

[9] Clamping devices are drives with toggle lever systems, e.g. as used when building vehicle bodies.

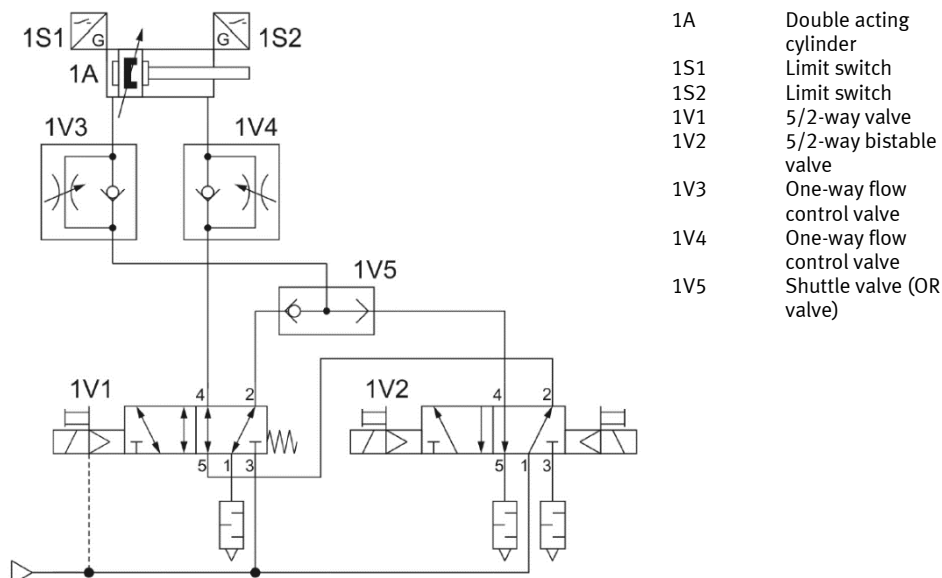| 1A | Double acting cylinder |
1S1	Limit switch
1S2	Limit switch
1V1	5/2-way valve
1V2	5/2-way bistable valve
1V3	One-way flow control valve
1V4	One-way flow control valve
1V5	Shuttle valve (OR valve)

Figure 11: Clamping device actuated by a monostable 5/2-way valve and a bistable valve

For experienced pneumatics specialists, the additional AND gate required due to the interconnection of the valves here is clear. The elegant implementation of such circuits requires highly flexible valve mounting systems.

Prevention of unexpected start-up at a high level (risk-reducing measures which require a two-channel structure)[10] can be implemented easily by switching the pilot air in accordance with figure 8/9.

If similar risk reduction requirements are made for both the extension movement and protection against unexpected start-up, this will have more extensive effects on the circuit. If risk reduction of the extension movement of the cylinder is to be achieved, there are 2 options[11]:

- Reversing the movement or
- travelling at reduced pressure.

Two-channel reversing of the movement cannot be implemented with just one (standard) valve[12]. The expense would increase accordingly. Extension with reduced pressure would comply with the design priority of ensuring safety. It would also be feasible but would also conflict with a possible demand for "Holding with full force in the end position". If we implement all of these requirements, the circuit would be as shown in figure 12.

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[10] The category 2 options are intentionally not mentioned or used, as this category requires special attention due to its requirements for mechanical applications.

[11] Stopping is not given further attention in this example; non-control protective measures (guards) are also not considered.

[12] Reversing the movement remains single-channel – ultimately, it depends on the spring return function of the switching element to the neutral position.

As you can see, this results in a relatively complex circuit. As a result of the expense and the unusual appearance, readers might wonder whether too much was added here. However, when you consider that the door (movable guard) of a machine panel (fixed guard) is to be driven by cylinder 1A, it soon becomes clear that precisely these requirements in the following sequence are necessary:

- When the door is open, it should not close automatically,
- If a person reaches into the closing area of the door as it closes, a certain crushing force is not to be exceeded and the door should open again. When the door is closed, it must be held closed by force and must not open automatically,

These features must be implemented with the corresponding safety functions:

- Closing movement with reduced force – implemented by 1V6 combined with 1V7 combined with protection against unexpected start-up for valve 1V2 combined with 1V5,
- Switching to mode "Hold door closed under pressure" via (temporary) actuation of 1V2 and 1V5 when the lower end position is reached,
- Remaining in the closed position via function "Hold door closed under pressure" combined with protection against unexpected start-up via non-actuation of 1V2 and 1V5,
  Opening of door when machine control is released via actuation of 1V2 and 1V5.
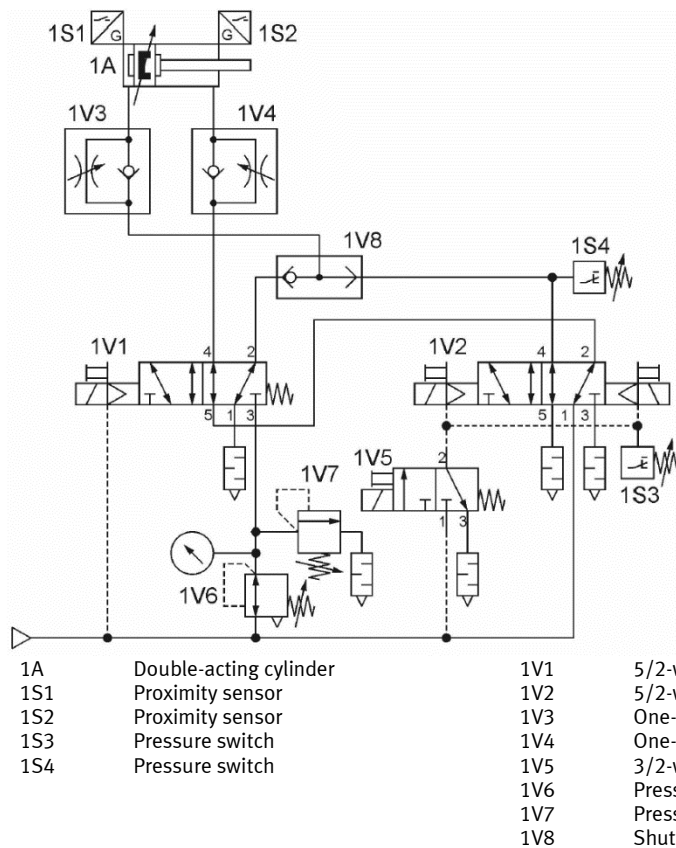
1A	Double-acting cylinder	1V1	5/2-way valve
1S1	Proximity sensor	1V2	5/2-way bistable valve
1S2	Proximity sensor	1V3	One-way flow control valve
1S3	Pressure switch	1V4	One-way flow control valve
1S4	Pressure switch	1V5	3/2-way valve
		1V6	Pressure regulator with display
		1V7	Pressure relief valve
		1V8	Shuttle valve (OR valve)

Figure 12: Actuating a drive with a monostable 5/2-way valve and a bistable valve with the additional requirements: extension with reduced pressure and protection against unexpected start-up

6   Summary

Requirements from the various operating states and state transitions can require additional circuit measures. As all changes are not free of reciprocal effects, it is recommended that all states and state transitions be determined and arranged in the sequence in which they occur at the start in order to ensure the systematic development of a solution. This list allows the requirement profile for the circuit to be defined and a solution to fulfil all requirements to be created on this basis. When we consider the conflicting requirements of the behaviour of the circuit which results from the requirements, status switching is essential. Used correctly, bistable valves are an elegant and possibly even the only solution for this purpose.

7   Literature

[1]   Standard DIN EN 60204-1:2006 – Safety of machinery – Electrical equipment of machines – Part 1: General requirements (IEC 60204-1:2005, modified); German version EN 60204-1:2006

[2]   Standard DIN EN ISO 12100:2011 – Safety of machinery – General principles for design – Risk assessment and risk reduction (ISO 12100:2010); German version EN ISO 12100:2010

[3]   Standard DIN EN ISO 13849-1:2008 – Safety of machinery – Safety-related parts of control systems – Part 1: General principles for design (ISO 13849-1:2006); German version EN ISO 13849-1:2008

[4]   Standard DIN EN ISO 4414:2011 – Pneumatic fluid power – General rules and safety requirements for systems and their components (ISO 4414:2010); German version EN ISO 4414:2010

[5]   Standard DIN EN 1037:2008 – Safety of machinery – Prevention of unexpected start-up; German version EN 1037:1995+A1:2008

[6]   Standard ISO 14118: 2000 – Safety of machinery – Prevention of unexpected start-up

Imprint