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DESIGN OF REPROGRAMMABLE, ROTARY, SINGLE-ACTUATOR MECHANICAL LOGIC VALVES FOR FLUID DIVERSION

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ABSTRACT

Fluid systems often require complex and plentiful valving which route a variety of input and output streams according to a system state. Many valves and actuators can create additional points of failure, maintenance, and cost. Multi-port selector valves are one solution which simplify complex configurations but are designed for a specific application. This custom design can create inflexibility and increased manufacturing cost when the user wishes to consider architectural changes or alternative applications. Modular, reconfigurable systems exist in fluid power systems (hydraulics, pneumatics), but few exist for larger, bulk flow applications. ***To address the issue of reconfigurability and simplicity within complex fluid valve architectures, we consider how one would design a single-actuator, reprogrammable, mechanical logic valve.*** *We consider design requirements for such a system, various strategies and concepts, and converge on exploring the design of a multiport, rotary valve. Geometric layout and performance models are proposed and parametrically analyzed to understand the design space, trends, and tradeoffs. This work lays initial foundation and exploration of modular, mechanically reconfigurable, rotary valves. We envision this design and architectural toolbox to be metaphorically similar to common, easy-to-assemble and reconfigure, standardized materials such as 80/20, push-to-connect fittings, and even Legos - but instead, with application to valve geometries.*

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NOMENCLATURE

n number of states
m number of inputs
l number of outputs
I_i the i-th input state vector
O_i the i-th output state vector
S number of stages in the design iteration
S_{max} the maximum number of possible stages
N_P number of nominal partitions per stage
N_S number of stages with nominal partitions
N_S' number of stages with partially utilized partitions
N_h number of holes per stage
r remainder of unused ports
θ_T total rotation for a full state machine run-through
θ_n incremental rotation for a single state change (one hole to another)
D input port diameter (in desired unit length)
C disc circumference
H disc height
V disc volume

1 INTRODUCTION

1.1 Reconfigurable logic valves in industry

Fluid systems commonly utilize valving including usage for isolation, regulation, safety relief, non-return, and specialty purposes [1]. One type in particular is the multiport valve. This valve is meant for combining, mixing, and controlling pathways of fluids such as in chemical reactors, industrial processes, oil and gas refinement.

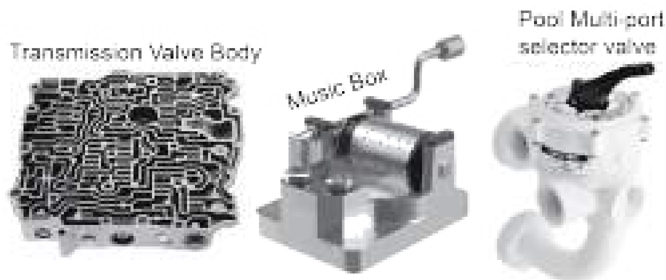

FIGURE 1. Inspirational prior art

One common example of a multiport selector valve exists in pool filtration. The valve on a residential pool filtration system is manually adjusted to select different states of operation, such as filtration, rinse, backwash, recirculation, winterization, etc. [2].

However, **adjustable states for multiport selector valves do not commonly exist in practice.** These valves are built to a specific function or state, having 3, 4-, 5- (or more) way control with fixed inputs and outputs. In essence, the flow paths for each actuation state (way) are fixed.

Fluid power applications employ modular, re-configurable valves; however, they are exclusively used for hydraulic or pneumatic applications. Many industries have shifted from line-mounted valves and sub-plate mounted valves to hydraulic integrated circuit (HIC) and screw-in cartridge valve (SiCV) manifolds [3,4]. These are modular, re-configurable manifold blocks that have individual slip or screw-in valves, which are combined to make one complete circuit. However, they are limited in channel size and may require multiple actuators to control. An interested reader can find some references for fluid power circuitry symbology here [5,6]. National Fluid Power Association (NFPA) is one organization that has defined standard symbols for describing various, fixed configurations.

Other current solutions to having reconfigurable, fluid diversion is simply by using many 2-way valves (closed, or open), controlled electronically such as via solenoids or motors. Such a system may have the flow logic built into software such as a programmable logic controller or microcontroller. However, this results in a significant amount of junctions and pathways which leads to increased volume, weight, and system cost. Such a system also involves the usage of electronic control and sensing, which may increase points of failure, complexity, cost of operation and maintenance.

1.2 Prior art exploring mechanically reprogrammable bulk-flow valves

There has been research exploring axially sealed (rather than radial) multiport, 3D printed injection valves in microfluidics due to their reduction of unused volume [7]. However, once the designs are printed, they are unalterable (although rapidly producible). The authors' devices use multiple single valves, each with their own actuator rather than coupling valve stages for operation with a single actuator.

Paratore et al. 2022 have reviewed real-time control of microfluidics pathways via pneumatic, electro-osmotic and magneto-hydrodynamic valves as well as hydrogen shrinkage/swelling, electro-wetting, and pressure distribution. These methods for dynamic control and alteration of flow paths involve complex actuation, materials, control strategies, and are mainly applicable for relatively small scale flows (order of magnitude $10-100\mu m$ channels) [8].

There have been some additional suggestions for adding logical flexibility by increasing number of flow directions on multiport valves. This can be accomplished by adding intermediate ports at smaller angles [9]. However, these are commonly only for a single input and multiple outputs such as a multiport selector valve for oil and gas.

1.3 Potential applications of reprogrammable, single-actuator mechanical logic valves

Adjustability of multiport valves for bulk fluid flow (alternative to fluid power) would be useful for reconfigurable fluids operations such as in desalination, in experimental setups such as in microfluidics, as well as when process parameters or flow configurations need to be rapidly altered without purchase of new or specialized componentry. Further examples could include fermentation, plating operations, chemical operations, beverage/food industry, and other water treatment processing plants.

An adjustable multiport valve could enable part standardization (less SKUs for specific applications), which may decrease the cost of architectural changes and enable ease of maintenance.

Single-actuation of multiport valves can additionally reduce complexity and modes of failure that may arise from multiple, cooperative actuators. However, while simpler, it also creates a single point of failure for an entire system.

1.4 A design tool for mechanically reprogrammable, rotary, multiport valves

A question remains: what is the architecture and design of a single-actuator, reprogrammable, mechanical logic valve for larger-scale flow mixing and diversion (rather than hydraulic or pneumatic power) applications?

In this work, **we propose a generalized architecture and design tool to generate reconfigurable, rotary, multiport**

valves for any set of desired inputs and outputs associated with a state machine.

We first considered a variety of potential concepts for mechanical logic valving (Section 2.3), and then down selected to a rotary geometry (Section 2.4). The design tool created is specific to this geometry. Some detailed design aspects are left generalized in the design tool as user inputs (e.g., o-ring friction coefficient in Section 3.2). Our detailed design examines valves on the scale of inches in diameter.

We explore a range of potential input parameters to explore the general behavior and trends within the design of such a valve (Section 4). We additionally constructed a preliminary prototype to test the sealing concepts, torque, and flow of the proposed architecture for a simple case study (Appendix B).

This deterministic design framework for multiport, rotary valves has the potential to enable rapidly reconfigurable, standardized, mass manufacturable, single-actuator valves. We aspire for the components, design of these valves, and their use to be metaphorically similar to Legos, Erector Sets, 80/20, or other easy-to-use building blocks and tools - but for fluid flow.

2 CONCEPTUALIZATION

2.1 Functional Requirements

First and foremost, we require the valve system to be **adaptable to different numbers of inlets and outlet fluid streams, as well as different states** for each of those inlets and outlets. To elaborate, each inlet and outlet may be open or closed in a particular state; in another state, the inlets and outlets would have a different on/off status.

For instance, a valve system in a batch chemical process may require two inlet streams of alkali and water, and output a single mixed stream to a reactor in a filling state. Then, the next state would be switching the alkali stream off and instead adding water to a different tank (i.e., a different outlet). The states would exist as follows: [Alkali, Water, Reactor, Tank] = [1, 1, 1, 0] in the first state and [0, 1, 0, 1] in the second state.

Secondly, **minimizing or eliminating leakage of fluids** is fundamental to valve efficiency, reducing material waste, preventing undesirable mixing or flow (which impacts safety and feasibility with hazardous materials or ultrapure processes such as pharmaceutical manufacture). Positional accuracy will be important and relevant for understanding valve leakage, as well as reducing energetic losses via pressure drops.

The functional requirements for such a valve system are also driven by **manufacturability and cost**. Minimizing the number of unique components, and number of features on the components is relevant to increasing manufacturability and decreasing cost at scale. Minimizing part volume is also important for reducing costs associated with material.

Energetic efficiency is another important feature related to the actuator power and the pressure drop across the valve. Minimizing the torque required to actuate the valve decreases the power required to actuate (reducing actuator cost), decreases valve wear related to friction (increasing lifetime), and can increase the actuation speed or ease of actuation by a user if it is manually operated.

An additional consideration is **durability and reliability**. The valve must withstand the pressure required by the fluid application. It should be sufficiently reliable and have sufficient lifetime, and may operate in harsh environments such as with corrosive chemicals and/or with variations to temperature and weather.

Depending on the application, a failure mode or designated failure state when power is lost may also be important.

The table in Appendix A lists potential functional requirements a user may consider. We aimed our initial focus on the functional requirements of reconfigurability while minimizing leakage and minimizing the number of unique components. We also aimed to generally predict torque, power, and material cost of the valve system. Prediction can enable the optimization of these performance parameters against the cost of components and leakage, with the constraint of reconfigurability.

2.2 Strategies

To create a single-actuator, multiport, reconfigurable system, **various strategies for motion/actuation, programming, and flow geometry** were considered.

2.2.1 Actuation

Linear actuation of valves such as via a lead screw, traction drive, solenoid, ball screw, and rack and pinion were considered. Rotary actuation via a screw - or even a hybrid of both rotation and translation - were actuation paths considered for the valve movement with inspiration from dog box transmissions, Shane Wighton's tactile sensing device for the blind [10], and more.

2.2.2 Logic

Programming of the state machine or mechanical logic (i.e., at what point flow should be open or closed, where the flow shall travel) was also considered as another strategic module. Various fluid [11–13] and mechanical logic systems exist [14], with some inspiration including latch-rod control logic [15], Charles Babbage's difference engine [16], Jacquard loom, rotating programmed cylinders such as barrel cams, pinned cylinders such as in music boxes magnetic drums, and early water and barrel organs [17], lobes on plates, camshafts, and intermittent selector mechanisms [18]. Some additionally interesting valve structures include automatic transmission valve bodies. Prior art with a rotary barrel controlling multiple hydraulic devices was also found an interesting logic and actuation methodology [19].

2.2.3 Flow Geometry

Finally, various valve strategies were considered – from commonly employed valves such as ball and plug valves, to flexures, flaps, and hinges that could restrict and redirect flow paths. Other considerations included coupling flow from other channels as well as considering the modularity of the system. Additionally, rotational or linear reversal mechanisms were considered (such as a differential with a coupled-speed side gears, or a planetary gear system with a rotationally free ring output).

Some fail-safe mechanisms were ruminated but not explored in this work, which included winding rotational springs with triggers, a capacitor and limit switch, pressure accumulator, and indexing clutch.

2.3 Concepts

A number of concepts were generated, combining different permutations of the aforementioned strategies. Some of the generated concepts are shown in Figure 2.

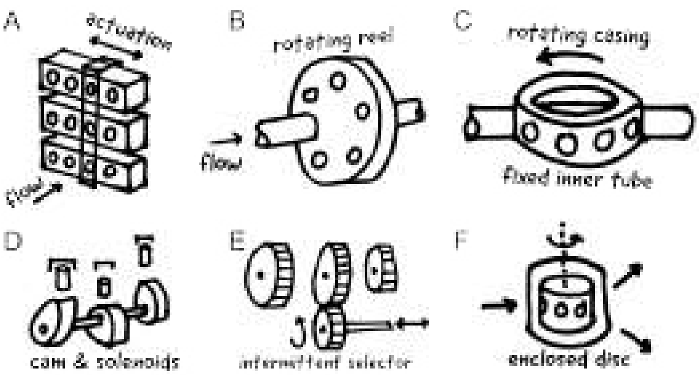

FIGURE 2. Example concepts

For instance, a linear rail of inlet and outlet ports, moving along a carriage of open or closed plugs (Fig. 2a) While simple, concerns existed regarding straightness and flatness error which could be accentuated when there are many states, inlets and outlets. Additionally, this concept would not allow for channel mixing – only individual valve control like a solenoid valve.

Figure 2b-c consider fixed tubing, with rotating plugs selectively opened or closed about the fixed tubing. However, coupling the actuation motion of these and ensuring sealing and preload appeared mechanically complex.

Figure 2d examines the usage of a camshaft, where the rotation and/or linear displacement of the cams could cause selective opening or closing of solenoids. Ultimately, this was more viable for solenoids acting as pneumatic triggers for the valves and we decided in this study to examine designs more readily compatible with electrical actuation.

Figure 2e examines a similar principle, but with a linearly translatable gear which selects and actuates (via rotation) a designated set of individual gears. These individuals gears may be linked directly to valve(s) or other logic mechanisms. While viable, the design appeared complex in control and in the number of components.

Finally, Figure 2f explores the usage of an enclosed disc with selectively open or closed ports – in essence, a ball valve with multiple holes that may be selectively covered or left open, rotating in small increments according to the number of holes on the disc diameter.

Ultimately, the enclosed disc concept (Fig. 2f) was chosen because of its ability to scale with increased amounts of states and logical complexities. This can be accomplished by increasing the diameter of the cylinder as well as by coupling the disc to subsequent stages (other discs) above or below. Additionally, the sealing mechanism of this valve could be similar to commonly utilized ball valves, which have significant literature, are low-cost and used widely in industry. They boast good sealing, simplicity, and relatively lower pressure drop in contrast to a solenoid valve.

2.4 Chosen Concept

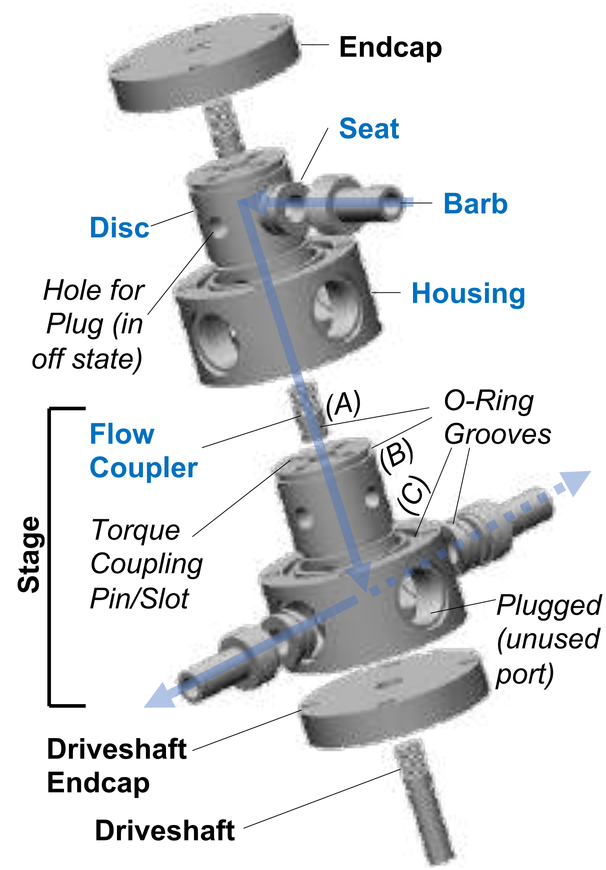

FIGURE 3. Multiport, reconfigurable, rotational valve concept

Figure 3 illustrates a multiport rotational valve mechanism.

It involves a series of stages which consist of a disc, a housing, and any number of seats and barbs (dependent on the number of inlets and outlets desired on that stage). The intended flow path of the prototyped example later discussed is in blue, but the concept can be extrapolated to a multitude of reconfigurable flow paths as well as additional inputs and outputs.

The disc rotates within a fixed housing, and each incremental rotation leads to a new state (where a state is a set of inlet and outlet conditions, such as defining inlet 1 as closed, outlet 2 as open and outlet 3 as closed).

2.4.1 Disc

The disc design consists of a series of holes which either couple flow to different stages (on the top and bottom, flat faces) or interface with the input and output ports (on the side, curved faces). The disc is composed of radially axisymmetric, tapped, tapered holes (on the curved faces) where plugs are to be placed. These plugs either allow or block flow to the corresponding barb when rotated into position.

The disc also consists of a tapped, tapered hole on the top face for inserting the flow coupler. On the other face, the disc consists of a straight hole where the flow coupler's O-ring (denoted (A) in Fig. 3) interferes and creates a seal, allowing passage of water between stages without leakage.

The disc additionally is composed of circumferentially seated O-rings (denoted (B) in Fig. 3) (on the curved face), which slide against the housing and provide a barrier to any leakage pathways between the open plugs on the discs and the next stage. While this seal is not absolutely necessary, it does offer redundancy; the leakage pathway between the housing and the discs cannot reach the outlet barbs when the plug is closed, so long as the seat is properly sealed.

Finally, to transmit torque from one stage to the next, press fit pins are placed on one the top face of the disc and slots are placed on the bottom face. These slots are larger (clearance) than the fitted pins, and a small gasket is placed over the pins to secure and elastically average the positions between the two discs. This aids the positional accuracy (plug to port/barb alignment) of a valve system with many stages. A future design could include three parallel slots, with two inner walls that bend, acting as springs to accommodate the pin and reduce complexity.

2.4.2 Housing

The housing consists of larger threaded inlets for placement of the threaded pipe/tube or hose barb, allowing for inlet and outlet ports. There exists a smoothed portion at the end of the barb proximal to the disc center where the seat is able to slide and seal against the disc.

The housing additionally consists of an O-ring face seal on the top circular face (denoted as (C) in Fig. 3), and a flat face on the bottom face. This is done to seal the valve compartment and prevent external leakage. Clearance holes are incorporated to create a bolted joint with all of the stages on top of each other. Note, the housing is the same height as the disc; if this is not the case, positional accuracy errors may stack up and discs may be shifted upward or downward in practice. The diameters of the stacked housing and diameters of the discs must also be equivalent. The positional accuracy stack-up error could be avoided by implementing compliance on the disc and housing faces (top and bottom) such as a thin gasket. Future work could also consider alternating sets of countersunk holes and threads between each unit to avoid interference with the next and to make disassembly easier (one module at a time could be taken apart).

The seat-disc interface is set to a known preload by compressing a gasket of known stiffness between the barb and seat. This gasket also prevents a leakage pathway between the seat and the barb. The seats' main purpose is to provide a seal that prevents leakage from the gap between the disc and housing to the inlet or outlet barbs. It is thus fundamental that the seat is closely conformed to the disc shape. Often, smooth, softer surfaces like polytetrafluoroethylene (e.g., Teflon) are employed. Similar types of sealing are often seen in ball valves.

The supporting cap exists to prevent leakage out of the housing and provide a place to constrain the coupler. The center hole on the supporting cap acts as a bearing for the coupler that is linked to the rest of the stages.

The driving endcap is characterized by a hole in the center that compresses a piston O-ring on the driveshaft. This is a fundamental but low tolerance fit, as the relatively small O-ring must prevent leakage from the housing, but also allow rotation; these are competing objectives.

The rotational valve features compatibility and modularity in adding or subtracting stages, in changing the system states via plugs, and in changing the number of I/O. It features only 5 unique parts that are redundant across additional stages (not including the driveshaft and endcaps). We do note, in this analysis we are coupling valves of the same diameter inlet and outlet; it would be interesting future work to explore adjustability of port diameter.

3 DESIGN FRAMEWORK

The general design framework for this concept reconfigurable multiport rotary valve is based on a set of geometric and performance-based user inputs. The geometric inputs are utilized to calculate all possible configurations in section 3.1. The performance inputs are combined with the calculated configurations to determine metrics of valve performance (applied torque, power, leakage, material cost, etc.) as detailed in section 3.2.

The geometric (left column) portion of this framework in Figure 4 assumes the rotary valve system discussed in the previous section, which may be conjoined to multiple stages. The geometric configuration only relies on the user's desired state machine and flow diameter (assuming a circular cross section flow path).

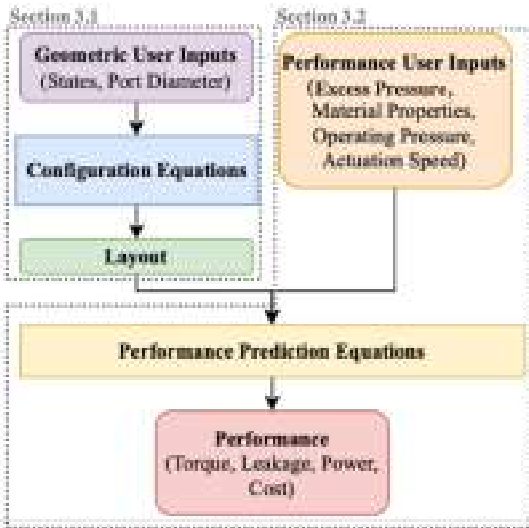

FIGURE 4. General design framework

The performance-based user inputs incorporate detailed design aspects such as user-defined O-ring stiffnesses and dimensional tolerances.

3.1 Configuration and layout determination

The designer specifies their desired vector of input and output ports and their states (either on or off), as well as the desired port diameter (i.e., flow channel size): these define the geometric user inputs. These are the only inputs needed to geometrically determine all possible rotary valve configurations, as well as rotation angles and geometric sizes (at a minimum approximation with relative sizes and calculations based on the port diameter).

Figure 5 details how all possible configurations were obtained. The algorithm first determines the maximum number of stages, S_{max}. The algorithm then iterates on designs within all possible numbers of stages, S up to the max, S_{max} (e.g., one stage, two stages, three stages… up to one stage per inlet, m or outlet port, l). If we can fit the same number of ports per stage (for instance, we have 6 total input and output ports and 2 discs, we can fit the same number of ports on each disc; 3 ports of input and/or output on the first disc, and 3 on the second) then we proceed to calculate partitions and holes per stage. If we cannot fit the same number of ports on each stage, we must determine how many stages will have an unused portion of their disc (via r) and apply an alternative approach to allocating partitions and holes per stage.

An example configuration output with inputs $I_1 = [1; 1]$, and outputs, $O_1 = [1; 0]$, $O_2 = [0; 1]$, is shown in Figure 6.

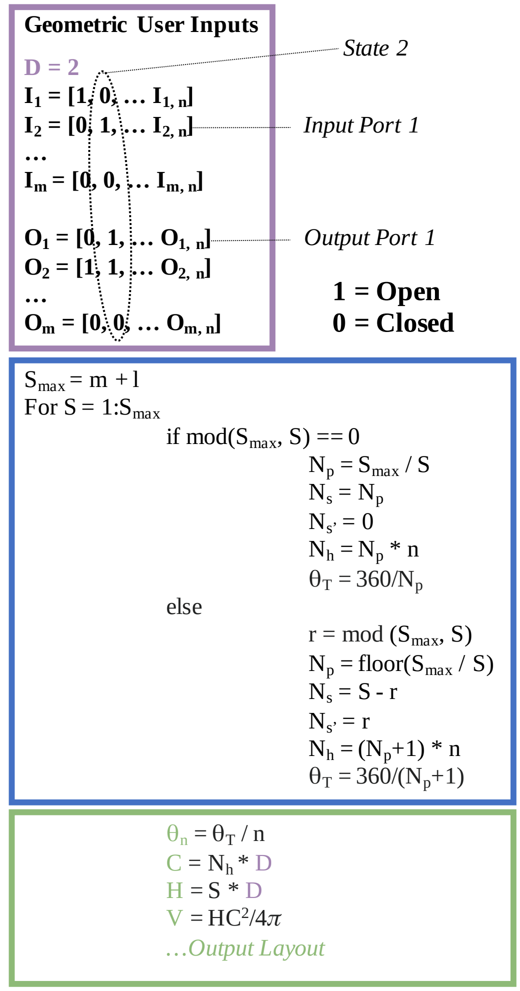

FIGURE 5. Configuration determination algorithm via port diameter and input/output state matrices, where 1 indicates open and 0 indicates closed

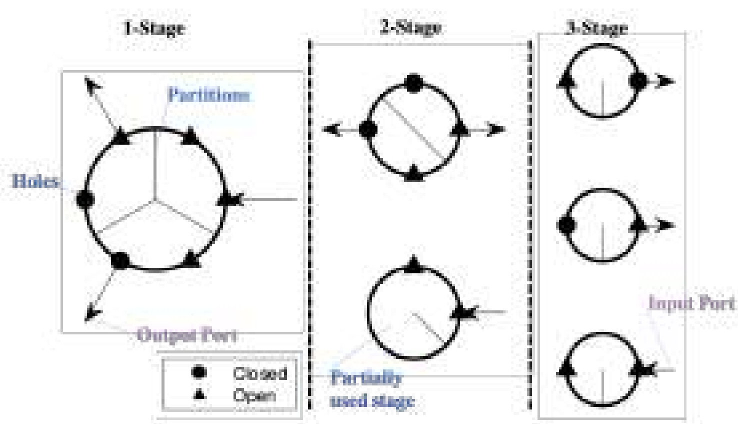

FIGURE 6. Example output of all potential design configurations (for each n-Stages) with one input, two outputs and two states.

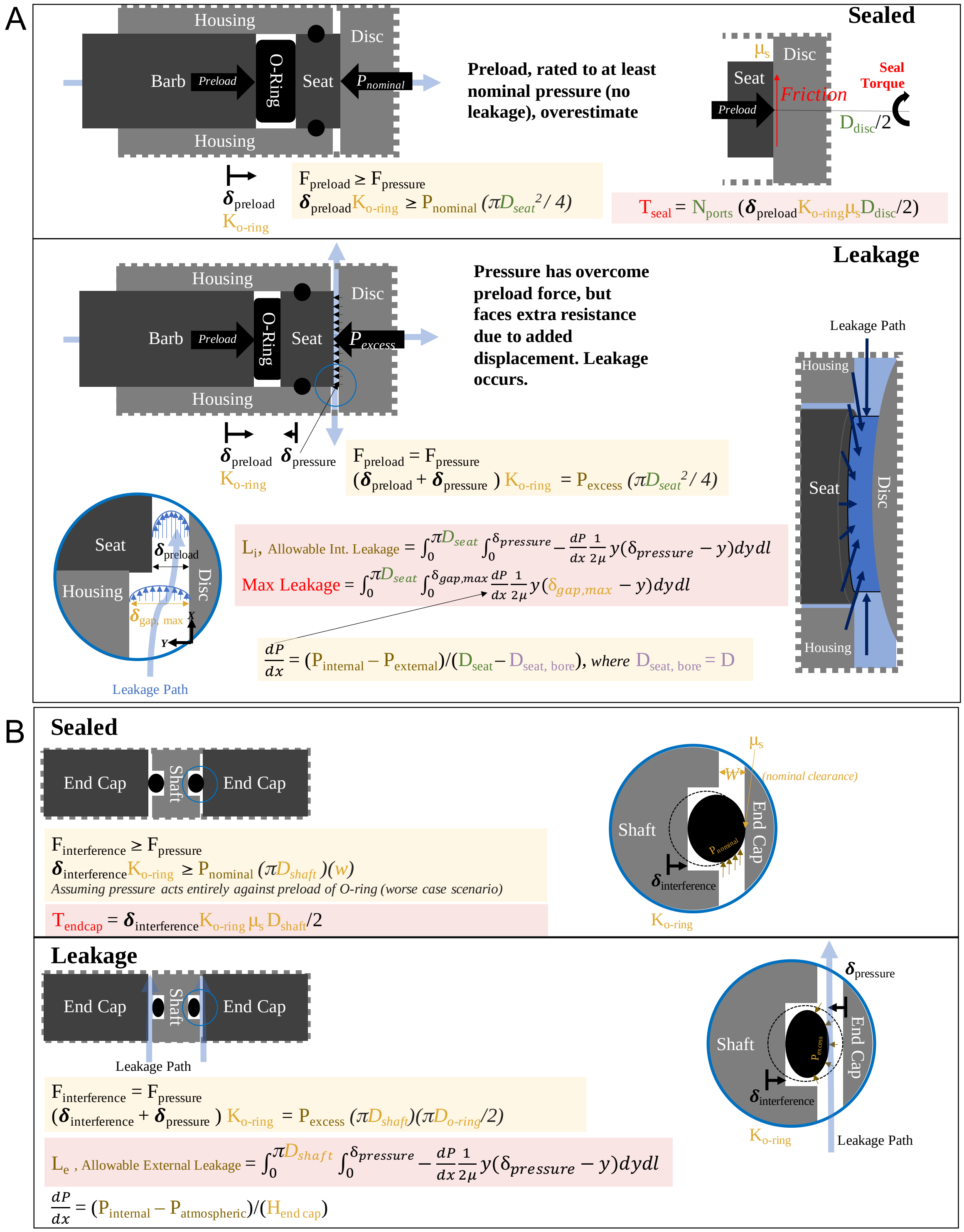

FIGURE 7. Analysis of leakage and torque produced within: (A) the seat-disc interface, and (B) the shaft-end cap interfaces. Where in (A), internal leakage originates, and (B) external leakage originates.

We can see generally, with a smaller number of stages, there are more ports (barbs) per stage or per disc, a smaller degree of rotations per state, and more partitions. In contrast, as we approach the limit for the maximum number of stages we may have, we observe only two ports per stage (the minimum), the largest amount of rotation per state change, and no true partitions (i.e., we can go back to our first state by completing the circle or spinning our 180 degrees).

3.2 Performance prediction

Some performance concerns include tradeoffs between operating pressure, nominal port diameter, leakage, power, torque, and cost. Some of these tradeoffs exist in sealing areas between the disc and the housing. Two of the sources we explore are the interfaces between the seat and the disc, as well as the O-ring seals at the end caps of the system (on the driveshaft and within the supporting cap).

Figure 7 details the derivations of the performance prediction equations, following the same color scheme as Figure 4.

3.2.1 Seat-Disc Interface

With some allowable internal leakage (or none at all) we can determine the minimum preload we must apply by screwing the barb into the O-ring, effectively deflecting and causing some force pushing the seat against the disc. This is based on geometry and the nominal operating pressure.

From this preload, we may then calculate the torque contribution (about the center of the valve, i.e., the stem torque due to start-up stiction rather than dynamic friction) using the O-ring stiffness, the static friction of the seat-disc interface (depending on materials chosen) and the disc diameter (calculated from our configuration determination, Fig. 5).

3.2.2 Shaft Interfaces

The O-ring seals on the driveshaft and on the supporting cap (each of the ends of the valve – the top and bottom) additionally contribute to the stem torque and prevent leakage to outside of the housing. In a similar fashion, allowable leakage can be applied and torque can be calculated using the desired preload (specified via interference between the O-ring, the shaft, and the end cap). Note that the interface deflection is a function of the O-ring cross sectional diameter, the shaft groove geometry, and the clearance between the shaft and the end cap.

If we are able to accurately calculate the stem torque and leakage contributions, we may propagate these amongst multiple stages and varying disc geometries.

We may finally predict the total static torque and power required to actuate the system, as well as estimate the cost based on material cost per mass (Fig. 8). We additionally may predict any leakage if the system is over nominal pressure or designed to

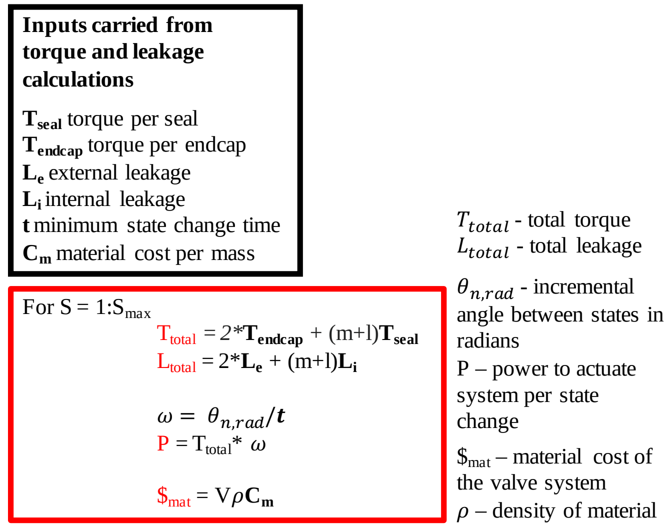

FIGURE 8. Performance predictions utilizing stem torque and leakage calculations

allow some amount of leakage per stage.

Future work could examine prediction of wear, driveshaft stiffness and diameter to meet the stem torque and actuator power necessary, positional accuracy, and more. A user-defined costing function could be then implemented (such as in error budgeting) to take into account these considerations and performance predictions and generate a recommended design.

4 PARAMETRIC ANALYSIS

A parametric study was done on this model for valve performance, and we examine the general trends and behavior of different potential design situations.

The values and assumptions applied for this exploration included: a speed of 1 second to change states (recall a state is the current setting or configuration of I/O, as open or closed for each port), that the seat diameter was approximated as the port diameter, friction coefficient for Teflon-PVC seat is 0.125, the stiffness of the 50A durometer O-rings used are approximately 14 lbf/inch of o-ring length for 20% crush. The friction coefficient between the O-ring and PVC is assumed to be 0.7. The gap between the shaft and endcap is approximately 0.01 inches. The dynamic viscosity of water is 9e-4 pascal-seconds.

We first examine how the power may vary with changes in the total number of inputs/outputs (or total number of fluid ports into the valve system) as well as with the number of stages employed for a given I/O system. Note, the lower right half of this matrix does not exist, as it is physically infeasible to create more stages than the total number of inputs/outputs. If the total I/O is the number of stages plus one, this is the upper limit for stages,

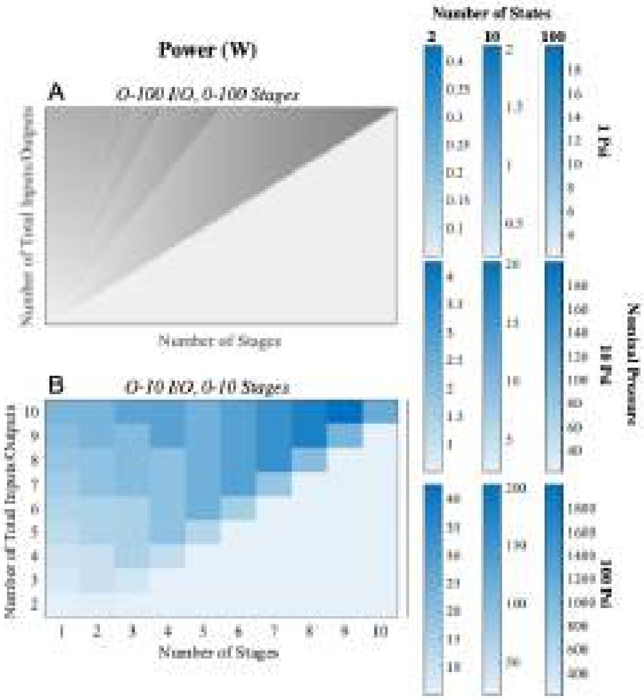

FIGURE 9. Power predictions where the colorbars in blue indicate the power scaling in watts for a 3 x 3 matrix of number of states (the columns) and nominal working pressure (the rows). The greyscale portion (Fig. 9a) is for showing general trends at higher number of stages and I/O (up to 100 rather than 10). The blue colorbars are only for Figure 9b. Darker regions indicate relatively higher power requirements for a state change.

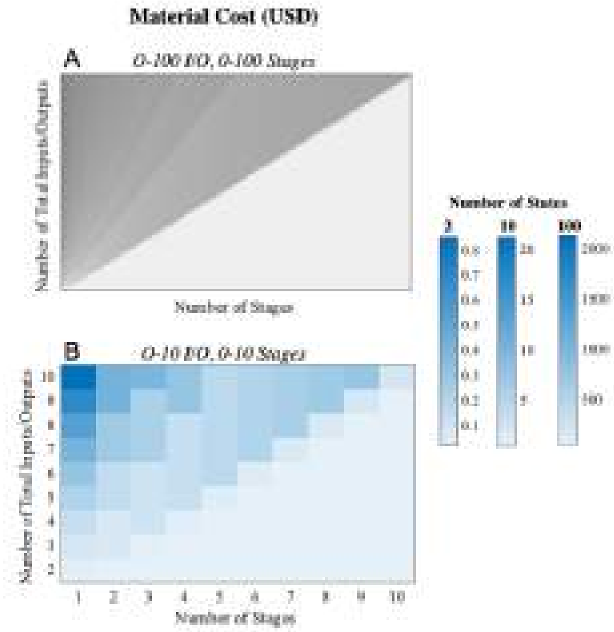

FIGURE 10. Material cost predictions where the cost (USD) is indicated the legend in blue, with variations in scaling depending on the number of states applied. Again, the grey region is for indicating general trends at larger I/O and stage ranges.

and each stage will have only two ports.

A heat map is shown in Figure 9, where the color indicates the associated power. The colorbars on the right hand side are in a matrix according to the number of states and nominal pressure input. The port diameter for this exploration was held constant and assumed to be 1 inch.

The greyscale portion (Fig. 9a) is for showing general trends at higher number of stages and I/O (up to 100 rather than 10). The blue colorbars are only for Figure 9b. Darker regions indicate higher power requirements for a state change.

Notice, the maximum power required occurs with high numbers of inputs/outputs, with stages indivisible by the total I/O count, and a high number of stages. This occurs due to the increased torque with high I/O and stages, larger circumference stages when partial stages occur (not completely filled with used ports), and larger degrees of rotation per state change when there are more stages.

Similarly, material costs are examined based on the volume of the part. We assume PVC for these calculations with a density of 1.38 g/cm^3 and cost of \$1.18 USD/kg. The same matrix of parameter changes (to number of states and nominal pressure input) as the power plot is examined here.

Material costs appear to be greatest with many I/O ports and few stages. This is related to the need for larger circumference discs in these conditions, as more ports must fit on a smaller number of stages (e.g., a single stage must fit all I/O).

Leakage is examined (both internal and external) for a variety of port diameters and excess pressures beyond a nominal operating pressure set to 100 psi (Fig. 11). The greatest amount of leakage during excess pressure operation appears to occur with lower numbers of stages. This is potentially linked to the larger circumference disc with only one stage.

Finally, we can see generally from Figure 12 the discrete variation in required rotation during state changes. When the number of stages is highest (closest to the total number of inputs and outputs), the degree of rotation during state changes is the highest. Conversely, single stage (and generally low number of stages) results in less rotation during state changes.

In summary, **high ratios of stages to I/O result in lower cost and lower leakage but higher required actuation power systems**. Conversely, low stage to I/O ratios (fewer discs) result in higher cost and higher leakage but lower power requirements for actuation.

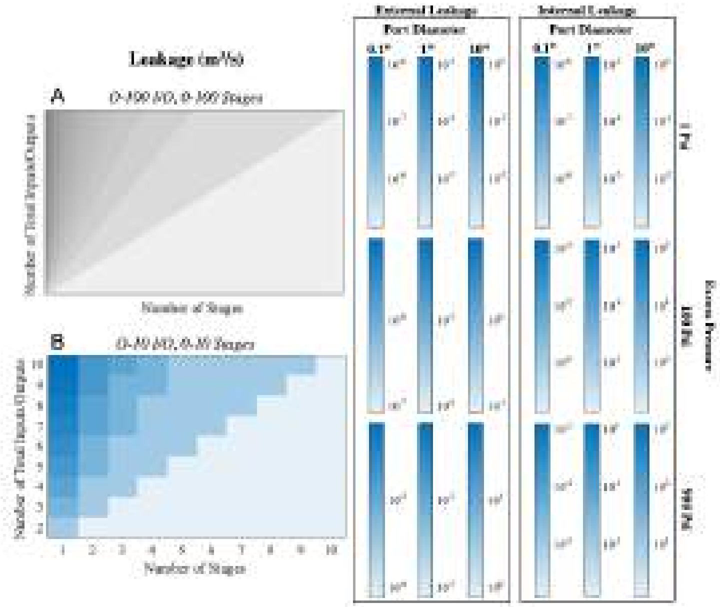

FIGURE 11. Leakage predictions where the leakage rate (m^3/s) is indicated in blue, with two 3 x 3 matrices showing the scaling of different port diameter and pressures, and each matrix indicates where the leakage originates from: internal or external. The grey plot indicates general trends for larger I/O and stage ranges.

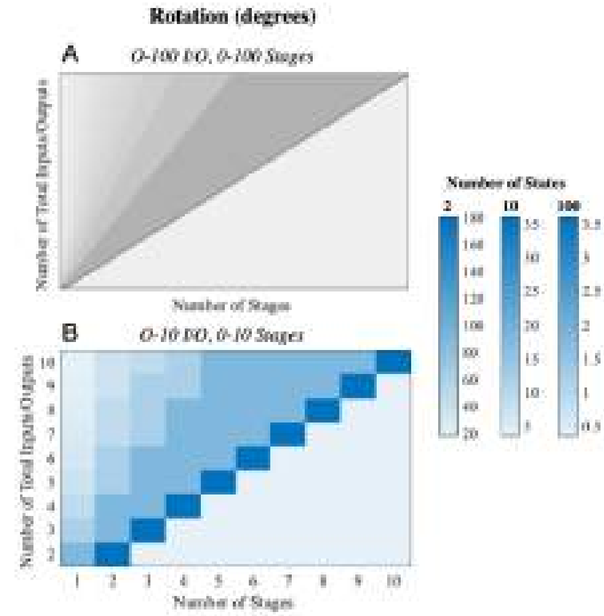

FIGURE 12. Rotation upon state change for different stage configurations, number of states, and number of input/output ports

5 DISCUSSION AND CONCLUSIONS

This work lays some initial groundwork for mass manufacturable, reconfigurable rotary valves. We provide a simple, deterministic design strategy that allows the user to input any desired flow mixing and/or diversion configuration (essentially, any state machine) and output all of the possible valve configurations and their performance tradeoffs (such as actuation torque versus leakage). We do note this is limited to fluids that may mix with each other; fluids which must remain isolated could be incorporated in future work, with blocked flow couplers between stages.

We conducted a parametric analysis on the proposed performance model for this architecture and find tradeoffs between required actuator power, cost, and leakage. Much of the behavior observed appears to arise because of variations in degrees of rotation during state changes (with higher degrees of rotation required for less ports per stage) as well as due to the discrete geometric nature of the design options.

It would be important to consider practical manufacturing implications when extremely small or extremely large valves are created. For instance, machining a very small tolerance (for instance, less than one thousandth of an inch) may be difficult on common commercial mill and lathe setups. This may be encountered when designing for valves with a very small port size (on the order of 0.01 inches). Additionally, the availability of O-rings or other gaskets at different size scales may be more or less difficult. For instance, in microfluidic devices (on the order of microns or less) that may employ this design framework, other gasket materials may need to be considered when designing. We imagine this framework could be initially applied to mid-sized (1/4" to 2" or more perhaps), multistage valving, with injection moldable components for production at scale. Many PVC ball valves are constructed using injection molding.

This work has much room for improvement. Aside from validating the proposed performance model with a prototype, we aim to add predictive features including positional accuracy of the valves, cycles to failure and wear, pressure drop through the valve system and more detailed cost modeling for this design tool. This could include a manufacturing cost model which could be related to the complexity or number of features in a mold, the size and tolerances, quantity of parts for an equivalent overall valve, and assembly time. Future work could additionally explore the design of a mechanical indexer which eases the control and positional accuracy requirements from a motor or human operator (in the case of a manually operated valve). Other ideas include incorporating mechanical fail-safes.

Simple, mechanically reconfigurable, multiport valves have the potential to bring flexibility to fluid systems. We hope this work can help bring Lego-like valves to reality.

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Appendix A: Functional Requirements

TABLE 1. Generalized Functional Requirements

Metric	Unit	Value	Justification
Mechanically reconfigurable	[-]	[-]	rapid adaptability to new scenarios
Leakage	%	0.5	Class II ANSI FCI 70-2 2006 (IEC 60534-4)
Actuation Speed	seconds	1 to 15	pneumatic to DC electric valve timing
Actuation Effort	force, torque	minimize	energy savings, ease of operator use, speed
Lifetime	Actuations	70,000<	similar to 1" industrial ball valves
Operating Pressure	Psi	45-60	nominal values for 1" industrial ball valves
Pressure Drop	[-]	minimize	energy reduction
Volume	m^3	minimize	to minimize material cost
Flow	liters per hour	related to port diameter	based on application
Complexity	number of actuators	1	simplicity and minimization of failure modes
Material compatibility	[-]	compatible to medium	water, chemicals, oil/gas, etc.
Manufacturability	num. of components	minimize	tool changes, molds, mfg. time

Appendix B: Preliminary Prototype Findings

A case study on the 2-stage example in Figure 5 was explored with the aim of prototyping the concept for manufacturability, leakage, torque and power.

We used a port diameter of ¼ inch, and the same input and output matrix or state/logic machine as in the example (Fig. 5). The valve was initially manufactured using stereolithography (SLA) 3D printing using a Formlabs 3L with Clear and High Temp v2 resin (Fig. 15). However, the material proved to be too brittle to tap/die cut threads and thus difficult to make any adjustments.

The valve was instead machined using conversational programming on a CNC mill and with a lathe. The valve was machined primarily out of cast acrylic because of its low cost and nearly transparent properties (when machined with sufficiently smooth surface finish). The seat was made out of Teflon for its low coefficient of friction and because it is commonly utilized in valve seat applications (such as in common ball valves). Additionally, the barb/ports were made out of PVC, as the acrylic proved too brittle and difficult to properly die cut threads. The fully assembled valve can be seen in Figure 13. Its components can be seen in Figure 14.

The initial prototype required significant torque to actuate due to the o-ring friction on the discs. A future iteration should consider the mechanism of torque transfer between the driveshaft and the first stage, and consider the driveshaft structural requirements (e.g., material, diameter). The system did not leak with applied flow rates of 300-2000 mL/min (and had according pressure drops of 3.5-11 Psi across the valve). This work is still ongoing, and we aim to characterize the prototype's performance and compare it to what we predict in the aforementioned modeling.

FIGURE 13. Valve assembly

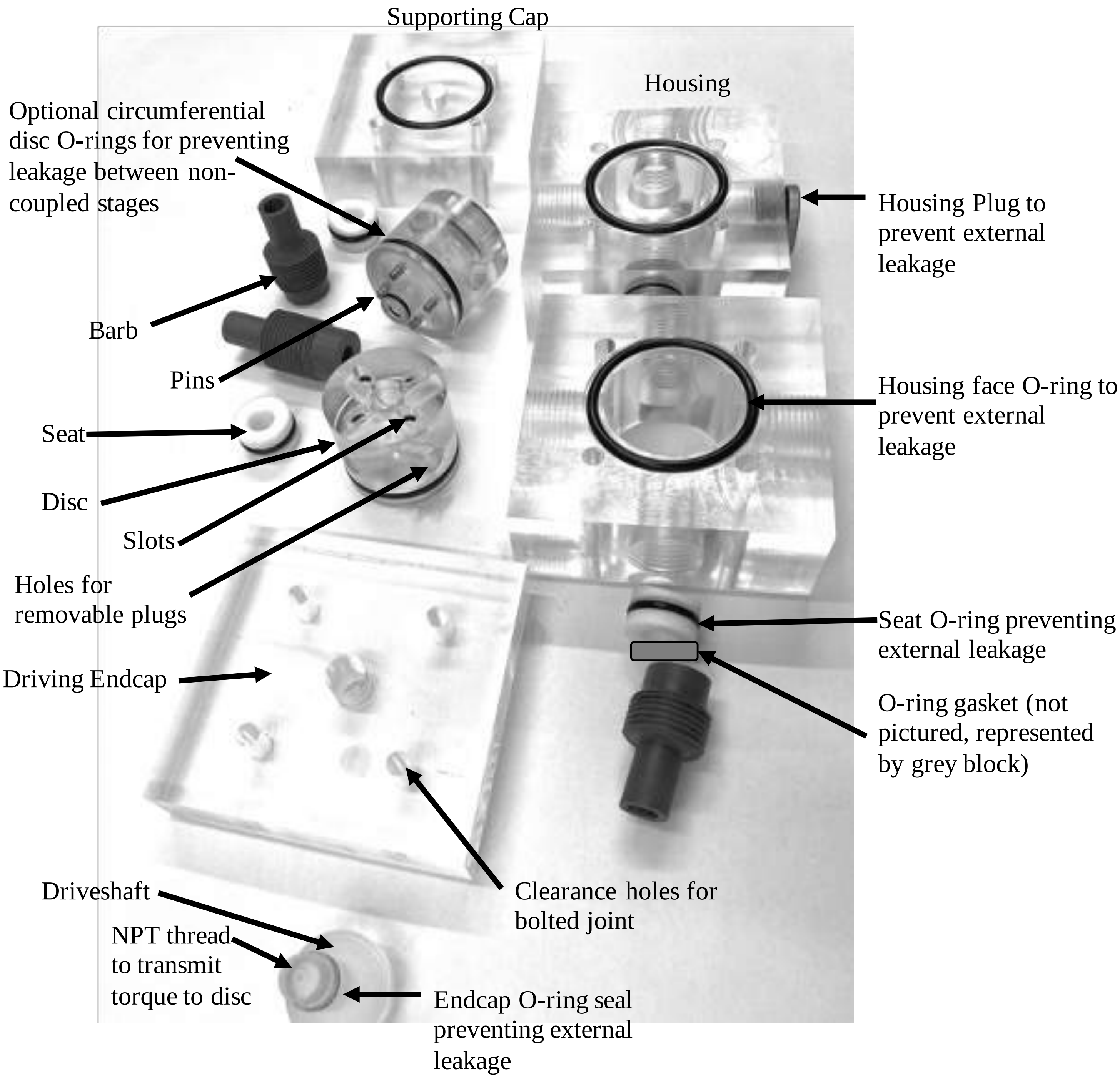

FIGURE 14. Valve components

FIGURE 15. SLA Prototype