

Article

# Experimental and Numerical Investigation of Six-Bar Linkage Application to Bellow Globe Valve for Compact Design

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**Abstract:** Bellow sealing in valves provides the characteristic of no emission sealing by extending or compressing within the elastic limit to operate the valve. To keep the motion of the bellow within the elastic limit, a long length of bellow is required, which increases the length of the shaft and height of the valve. Increased height restricts valve usage, especially for large sizes, due to the limited platform space. This study presents the application of a six-bar linkage to operating mechanism by replacing the reciprocating shaft in an attempt to reduce the height of the valve. The mechanism produced aims to reduce the input displacement while maintaining the output displacement in order to reduce the required bellow length. Graphical synthesis of the mechanism was carried out using Autodesk Inventor. The designed mechanism was then subjected to analysis using a simulation tool for the position, force, and flow analysis. The prototype valve with the application of the new mechanism was manufactured using additive manufacturing, which was later used for experimental testing. Application of the mechanism to the bellow valve reduced the required input by 75%, which as a result, reduced the height of the valve up to 50%. The force analysis depicted that the force required to operate the mechanism was approximately eight times higher than the conventional design. Flow analysis of the valve showed that the introduction of the new mechanism had no effect on the flow efficiency of the valve and the flow coefficient of valve remained the same. Application of the six-bar linkage to the valve control mechanism made the design of the valve compact when compared to conventional design in terms of height, which makes it more suitable for use in industry.

**Keywords:** globe valve; bellow valve; six-bar linkage; additive manufacturing; extending mechanism

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## 1. Introduction

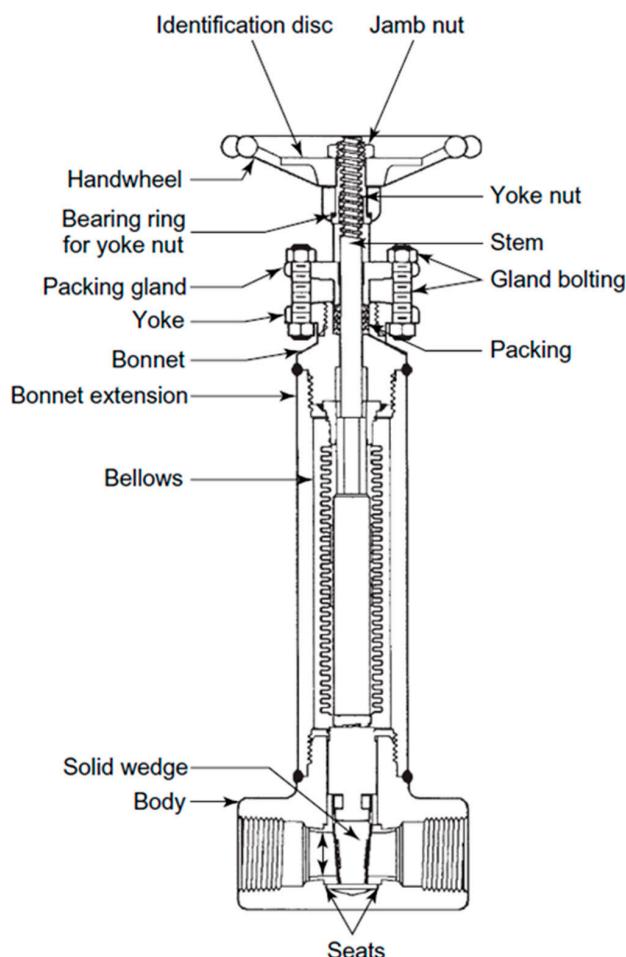
Control valves are commonly used devices for flow control in industries, with their use ranging from food industries to petrochemical industries. These control valves, especially the valves used in petrochemical industries, constitutes the major proportion of fugitive emissions from industries. According to studies by the European Sealing Association (ESA), valves account for up to 60% of fugitive emissions from a particular plant. Usually, valves with rising stems such as globe valves and gate valves tend to leak more often. A common reason for this leakage is the frequent operation of control valves that causes the stem and packing to wear quickly, thus allowing the emission paths to develop [1]. Regardless of how good the packing in the valve is, leakage still exists through the valve packing due to its design. Environment protection standards such as API 624 also consider leakage of up to 100 ppm as an acceptable emission [2]. In an attempt to solve this problem, a zero-leakage valve exists in industry known as a bellow valve [3].

Bellow valves use metal bellows for valve stem sealing, which removes the risk of emissions. Metal bellows provide the characteristic of no emission sealing by extending or compressing within

the elastic limit while allowing the required motion to operate the valve. The structure of the metal bellow valve consists of a metal bellow attached to a reciprocating shaft, that allows disc motion, and the bonnet of the valve. One end of the bellow is attached to the bonnet of the valve whereas the other end is attached to the stem. The bellow extends or compresses with the axial movement of the stem, thus providing the perfect sealing. The disadvantage of bellow valve sealing is that to keep the extension or compression of the bellow within the elastic limit, a long length of bellow is required to produce the required displacement. This in turns increases the length of the stem, therefore, increasing the height of the valve. The valve height for a one-inch valve can go up to 17 inches. This unusual valve height makes the design of the valve aesthetically unsuitable for most applications. This is the reason for the very low usage of bellow valves in industry [4]. This study presents the synthesis and analysis of a novel extending mechanism that addresses the problem of requiring of long length of bellow. The synthesized linkage will convert the small displacement of a bellow to a large displacement at the valve, therefore reducing the length of the bellow required to generate the desired motion. Introducing this mechanism helps reduce the height of the valve exponentially, thus making the design of bellow valves more suitable for use in industrial applications. The bellow valve working principle is shown in Figure 1.

Linkages are the most fundamental elements of mechanisms and machines. It is an assembly of a number of links and joints that generates the desired output motion in response to some specific input. The number of links possessed by a linkage gives the name to linkage, for example, a four-bar linkage consists of four links joined together to form a mechanism. A six-bar linkage, as the name suggests, is a single degree of freedom mechanism with six links and seven joints. A six-bar linkage can also be considered as a combination of two four bar linkages with two links shared. This assumption makes the synthesis and analysis of six-bar linkage less complicated by solving two four bar linkages [5]. There are several six-bar linkages that form the basis of various complicated mechanisms and can be considered as standard six-bar linkages. These standard six-bar linkages form a good starting point of linkage synthesis [6]. These include the Watt I six-bar linkage, Watt II six-bar linkage, Stephenson I six-bar linkage, Stephenson II six-bar linkage, and the Stephenson III six-bar linkage. Six-bar linkage also forms the basis of extending linkages used for magnifying displacements or forces. Various applications of six-bar linkages include a hand rehabilitation robot based on the Watt II linkage [7], leg mechanism based on the Stephenson III linkage [8], body guidance mechanism based on the Watt I linkage [9], and a furniture hinge mechanism based on the Watt I configuration [10].

Synthesis is typically the starting point of any mechanism design. For any given problem, the only thing known is the desired output or motion for some input. The design process usually involves the iteration between synthesis and analysis. So, to start the process, a potential solution is required to analyze, and then the solution is optimized based on the results. There are various available techniques for the synthesis of linkages to create potential solutions for mechanisms [11]. After the tentative mechanism is synthesized, the design is then analyzed to validate the linkage. The linkage is analyzed for the position of links and joints, at different inputs, their velocities, and accelerations. Linkages are also analyzed for dynamic forces to study the force propagation in the linkage, which can then also be used for stress analysis in the mechanism. Again, various analysis methods are available that can be used to analyze the linkage. A graphical approach can be used to draw linkages at various positions to determine position, velocity, and acceleration of output. Tools like CAD can be used to assist, but this approach involves a lot of work and can be very time consuming for complex mechanisms. Linkages can also be analyzed analytically by deriving general equations. Different approaches can be used to derive and solve these analytical expressions. Either algebraic representation or vector loop representation can be used to for the position analysis of a linkage [11].



**Figure 1.** Bellow valve working principle [4] (Reproduced with permission from Robert Flitney, Seals and Sealing Handbook; published by ELSEVIER, 2014).

Conventional/traditional manufacturing processes like forging and casting produce the highest quality parts in terms of surface finish and dimensional and geometrical accuracy. However, Additive Manufacturing (AM) technologies present tremendous opportunities and advantages over conventional processes [12]. AM provides the possibility to manufacture any design regardless of design complexity and allows for the production of integrated components. This is revolutionary towards wide open-mind designs without considering manufacturing constraints related to molding and machining. An improved globe valve design can be manufactured using additive manufacturing due to its capabilities to produce complex designs. From the study in [13], the additive manufacturing design of a globe valve showed the highest flow coefficient. This improved design can be used to manufacture valves with better performance. Pressure drop can be reduced with improved flow as a larger pressure drop creates the need for more mechanical strength in the valve body. Optimized pressure through better design such as optimized flow channels that can be reliably manufactured by AM can also reduce the overall weight of the valve. Layer by layer manufacturing in AM can enable us to manufacture a valve with structures like honeycomb, that are lightweight but still give the same mechanical strength as a solid part [14]. Valves can be tested on different internal structures to reduce the overall weight of the valve while maintaining its structural integrity. Additive manufacturing is potentially a motivating force in numerous industries towards advanced manufacturing initiatives [15]. The goal of this evolution is to produce better performing products with reduced costs and efficiency. Valves can be optimized by AM after improving their designs, which can result in better operating pressure ranges and improved flow rates through valves.

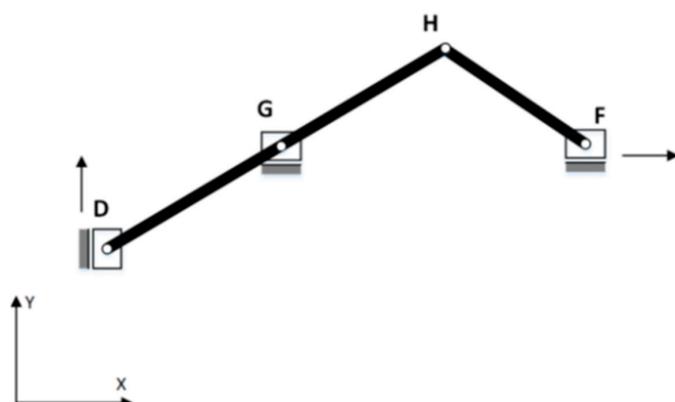
## 2. Materials and Methods

The methodology adapted for this research included kinematic and dynamic analysis of the mechanism application to a globe valve. The first phase of the methodology included the use of numerical simulation tools to study the application of a six-bar linkage in the globe valve. For the second phase, a prototype of the valve was developed using additive manufacturing. Later, the prototype was used to study the new design experimentally and to validate the simulation.

### 2.1. Linkage Application

As described in the introduction section, the problem of long bellow lengths exists in bellow valves to produce the required disc motion. Our goal was to minimize the length of the bellow required by using the mechanism synthesized to generate the same output motion at the disc. Rotation of a hand wheel generated the vertical motion in the valve stem, which was then attached to the disc. For sealing, one end of the bellow was attached to the bonnet and other to the stem. When the stem or disc moved upwards or downwards, the same amount of motion was also generated in the bellow. A much longer length of bellow was required, depending on the elastic limit of the material, to produce that motion.

Linkage was synthesized using type synthesis after modifications in the Stephenson III six-bar linkage. The linkage created formed three slider joints at points D, G, and F, allowing straight line motion only. When input motion was applied at point D, it moved along in the Y direction, causing the link DGH to rotate at point G and also to move joint G along the X direction. This movement will also create the same kind of motion in link HF, causing it to rotate and slide at joint F in X direction, thus producing a magnified motion at point F. The magnitude of the motion produced at joint F can be increased by adding more links between link DGH and link HF with the constraints to produce the same motion as of link DGH. The synthesized linkage is shown in Figure 2.

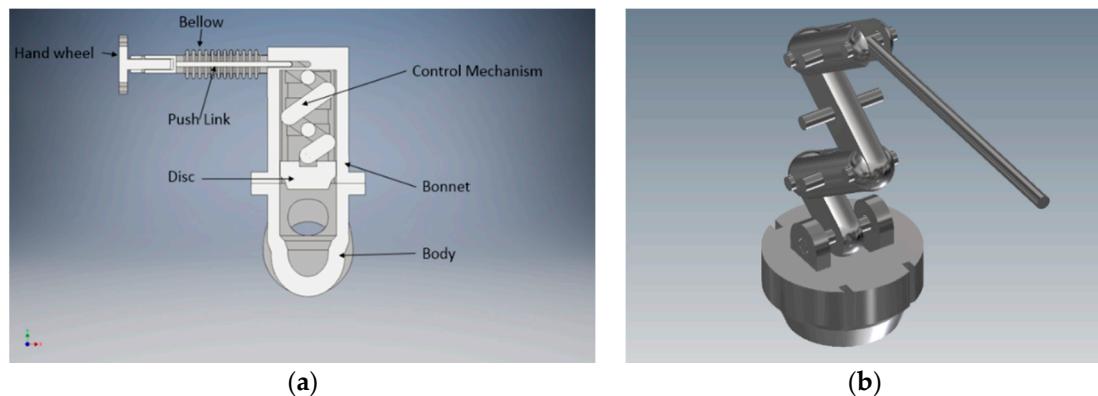


**Figure 2.** Synthesized linkage.

For this study, a commercially available bellow globe valve of size DN 25 was used. Bellow length in the valve was 305 mm, which made the height of the valve 380 mm long. To fully open and close the valve, the disc had to cover the displacement of 25 mm. Using the linkage synthesized above, a mechanism was designed for the valve that reduced the input displacement required by keeping the output constant. Reduced input will in turn reduce the length of bellow required for the valve. For this purpose, Autodesk Inventor 2017 was used to model the mechanism for opening and closing the valve.

Figure 3 shows the assembly of the designed mechanism in a globe valve. The output link of the mechanism was attached to the disc and the input link was attached to the bellow. By rotating the handle wheel, the rotary motion of the hand wheel was converted into the translatory motion of a rod by screw threads. The other end of this rod was attached to the mechanism and acted as the input link. The translatory motion produced in this rod was converted into larger displacement at the disc through the mechanism. A bellow was attached to the valve with one end connected to the rod and

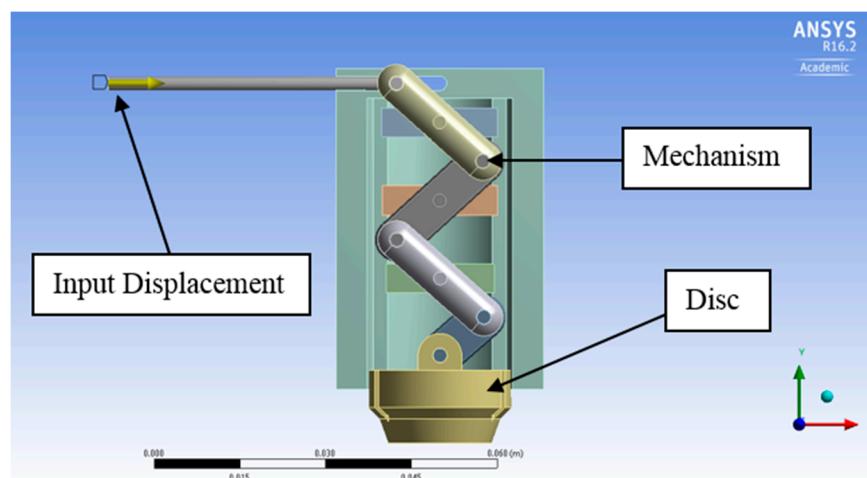
the other to the valve bonnet to provide sealing. The attached bellow compressed with the translatory motion of the valve while the valve was closing, and came back to its natural position while opening. Due to the small displacement of the input rod, the length of the bellow was significantly reduced.



**Figure 3.** (a) Globe valve with designed mechanism. (b) Isometric view of mechanism.

## 2.2. Numerical Modelling

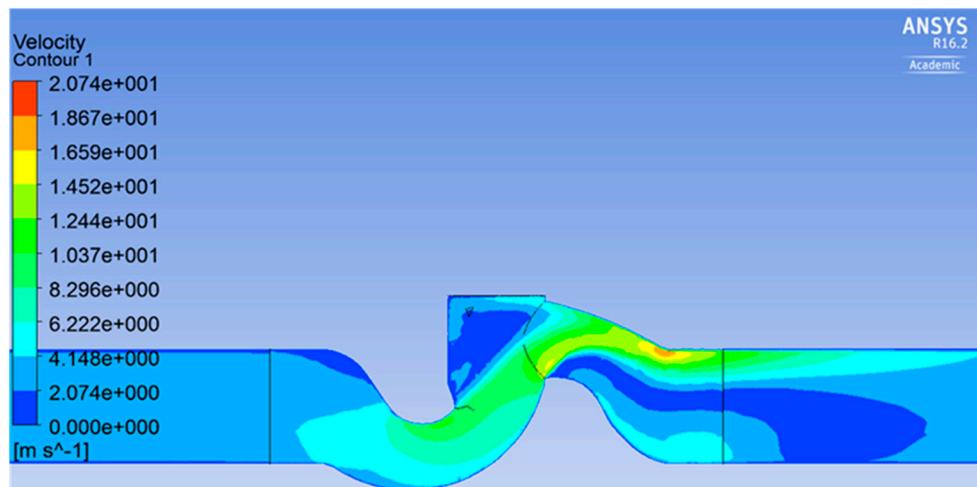
After the application of the synthesized mechanism to the globe valve, a valve with a new design was exported to the simulation tool, ANSYS Release 16.2, for the position, force, and flow analysis of the valve. Position analysis was performed to study the displacement of the valve disc with respect to the input displacement. Force analysis was done to calculate the actuation force required to operate the valve with the new mechanism. Flow analysis was carried out to see the effect of the new mechanism on the flow efficiency of the valve. A 3D CAD model of the globe valve developed using Autodesk Inventor was imported to ANSYS using the STEP file format. Joints and contacts were defined in the rigid dynamics module of ANSYS. The mechanism and all valve components were assumed to be rigid to study the dynamic behavior of the mechanism. Rigid dynamics analysis can be used to determine the dynamic response of an assembly of rigid bodies linked by joints and springs using implicit, Runge–Kutta functions. In a rigid body solver, no stresses and strain results are produced, and the solver only takes forces, displacement, moments, velocities, and acceleration into account. Input displacement is applied at the push link at regular intervals to measure the output displacement at the disc. The simulation model for position analysis is shown in Figure 4.



**Figure 4.** Simulation model for position analysis.

The extending mechanism does produce the magnified motion, as is obvious from its name, but comes at a price. The extending mechanism also reduces the force at the output compared to the force applied at the input. Therefore, the next step was to perform the force analysis on the designed mechanism to calculate the force required to actuate the mechanism. For this purpose, the valve design with applied mechanism was subjected to rigid dynamics analysis. Boundary conditions were applied to represent the real-life conditions including the fluid pressure in the valve acting on the disc, and the input force required to move the disc.

For the flow analysis, a 3D model of the flow path through the valve was extracted. Meshing for the extracted model was done using ANSYS meshing. The grids used were a combination of structured and unstructured. A structured grid was generated for sweepable bodies which are the upstream and downstream flow across the valve, whereas an unstructured (tetrahedron) grid was used for the valve flow. Investigation for grid independence was performed using a grid with 200,000 elements. All valve and pipe boundaries were denoted as no-slip velocity conditions, which implies that the relative to boundary fluid velocity was zero. The inlet and outlet of the flow profile were set as the pressure type, and pressure difference was assigned between the inlet and outlet. Initial conditions were set to standard temperature and pressure conditions (Pressure: 1 atm, Temperature: 25 °C). Steady state analysis was performed using incompressible flow type. The turbulence model was used to study the flow behavior in the governing equations. In this study, the standard k-epsilon (K- $\epsilon$ ) turbulence model with two equations was used. The process to select the turbulence model was based on a comparison of the various available studies on turbulence models for engineering applications. In the model under consideration here, the flow was turbulent with a high Reynolds number and our point of interest was the outlet flow velocity. The k-epsilon model is the most suitable model for the said case as studies have shown that the model is the most widely used for fully turbulent flows. It is also easy to implement and computationally cheap. In contrast to the k-epsilon model, the k-omega model is more suitable for near wall functions and low Reynolds number models. The flow velocity profile through the valve is shown in Figure 5 with an applied pressure difference of 50 kPa across valve.



**Figure 5.** Fluid flow through extracted fluid profile of valve.

### 2.3. Experimental

The use of additive manufacturing methods in the design process can quickly produce working prototypes. These prototypes can be used as an effective validation tool, both functionally and aesthetically. This helps in finding flaws at the testing stage and ensures a better product. In this study, fused deposition modelling (FDM) technology was used to develop a prototype of the valve. A Ultimaker 3 3D printer was used to manufacture the prototype. Acrylonitrile butadiene styrene

(ABS) material was used for 3D printing as it provided better strength when compared to the other available materials in the printer. For the support structures, Polyvinyl alcohol (PVA) was used.

To facilitate the manufacturing and assembly of the valve, the prototype was manufactured in three steps. In the first step, the valve body was manufactured. For ease of assembly of the body onto the testing rig, a base plate was added. The second step included the bonnet fabrication. The bellow in the bonnet was replaced with a cylinder through which a push rod could move. This is because the material used (ABS) does not provide enough elasticity to produce a functional bellow compared to metals. The third step of manufacturing was to make all of the internal components including the links, disc, and push rod. All components were printed as separate parts to be assembled together.

Keeping in mind that the prototype will be used for experimental analysis, design changes were made to allow for the convenient mounting of sensors on the valve to collect experimental data. The bonnet design was edited to place the force sensor between the handle and push rod. Connectors were added at the end of the valve to mount pressure gauges. After finalizing the design to be manufactured, the design was imported to Ultimaker Cura for pre-processing using an Standard Tessellation Language (STL) file format. Ultimaker Cura is a dedicated software for Ultimaker 3D printers that provide pre-processing options such as customized initial parameters, support structures, and build orientation. Parameters used for 3D printing are tabulated in Table 1.

**Table 1.** Process parameters for 3D printing.

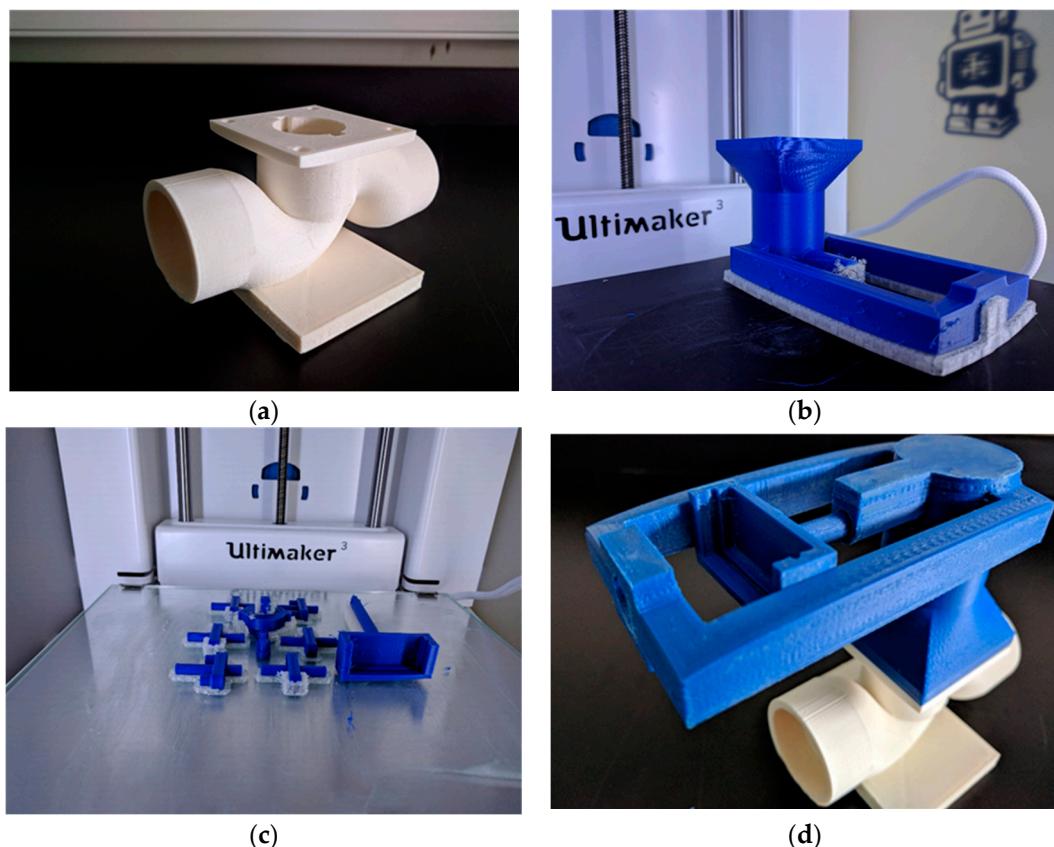
Process Parameters	
Printer Resolution	0.1 mm
Layer Height	0.2 mm
Wall Thickness	2 mm
Infill Density	100%
Print speed	60 mm/s
Travel Speed	250 mm/s
Printing Temperature	240 °C
Build Plate Temperature	80 °C

The prototype was printed in three steps: the valve body, bonnet, and components. One hundred percent infill density with resolution of 0.1 mm was used to print all parts to obtain the maximum strength. The total time taken to print all parts was 48 h. After the successful manufacturing of all parts, some post processing operations were performed. Post processing only included the removal of support structures by immersing the part in warm water. As built surface finishing was used. No finishing treatments were applied after manufacturing. The 3D printed parts provided good dimensional accuracy for testing. To remove the support structures, all parts were immersed in water, as the support structure material is water soluble. Filing was done, where required, to remove the extra material for assembly. All printed parts were assembled together to obtain the final prototype. The manufactured valve components and assembled valve is shown in Figure 6.

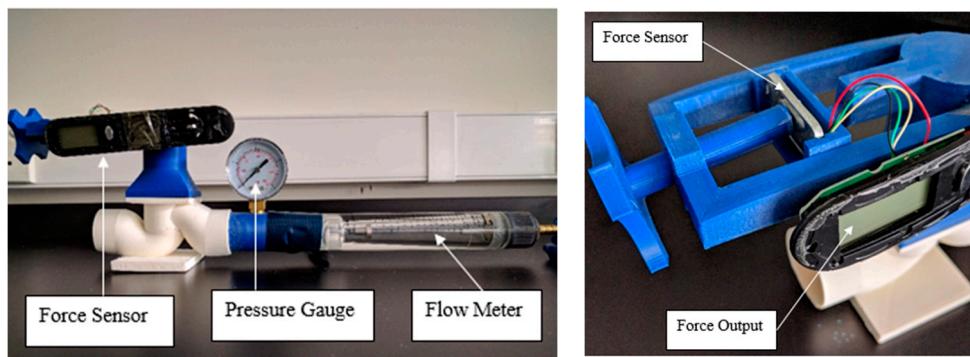
For this study, the bellow was assumed and produced as a solid cylinder as FDM cannot provide enough elasticity for the bellow function. Force on the valve disc was assumed to be equal to the fluid pressure acting on the disc. Additionally, the dimensional accuracy of the printed parts was assumed to be similar to the modelled part with a difference of 0.2 mm. However, these assumptions do not affect the accuracy of the simulation and experiment as the bellow profile does not affect the flow profile of the fluid through the valve; there will be less force acting in real life due to pressure losses and geometric tolerance does not have a significant effect on flow.

After fabricating the prototype, the prototype was subjected to experimental testing for position, force, and flow analysis. Sensor and gauges were mounted on already manufactured mountings during the manufacturing process. For position analysis, the input displacement was applied at the push link with a hand wheel. Threads between the handwheel and bonnet were created with the pitch so that one turn of the hand wheel produced 2 mm of linear displacement. The input displacement

was applied with intervals of 2 mm, from 0 to 10 mm. The output displacement at the disc was measured corresponding to each interval of the input displacement. To measure the actuation force, the strain gauge was used to measure the applied force. The strain gauge was mounted between the hand wheel and push rod to measure the compressive force to actuate the mechanism against the fluid force. The strain gauge was calibrated by applying known loads and was compared with the strain gauge output. The accuracy of the measurement was within 1 N. Force was measured at four different positions of the disc, when the valve was opened 75%, 50%, 25%, and 0%. The force reading was taken against the fluid pressure ranging from 10 to 50 kPa. The selected pressure range was kept relatively low as the material of the valve was plastic and could not withstand the high pressures when compared to the metal valves. To determine the effect of the mechanism on the flow efficiency of the valve, the flow coefficient of the valve was determined. The flow coefficient is dependent on the pressure drop across the valve and flow rate through the valve. The pressure drop across the valve was controlled by controlling the inlet pressure from 10–50 kPa while keeping the outlet pressure constant at atmospheric pressure. A pressure regulator was used to regulate the inlet pressure. The pressure gauge was mounted at the outlet to measure pressure and the flow meter was connected in series at the valve outlet to measure the flow rate through the valve. Water was used as the fluid medium. Three parameters were tested: the position, force, and flow coefficient. Parameters were repeated for five different pressure values at the inlet. There were no significant variations between the measurements and a similar trend was observed in all measurements. The test equipment used was reliable enough to not affect the results. As the number of parameters tested were few, the design of the experiments and statistical analysis was not considered for this research. Due to the new concept of valve design, no standard could be followed for the testing. The experimental design for this research was custom built. The experimental setup is shown in Figure 7.



**Figure 6.** (a) Manufactured valve body. (b) Manufactured valve bonnet. (c) Manufactured mechanism components. (d) Assembled valve.

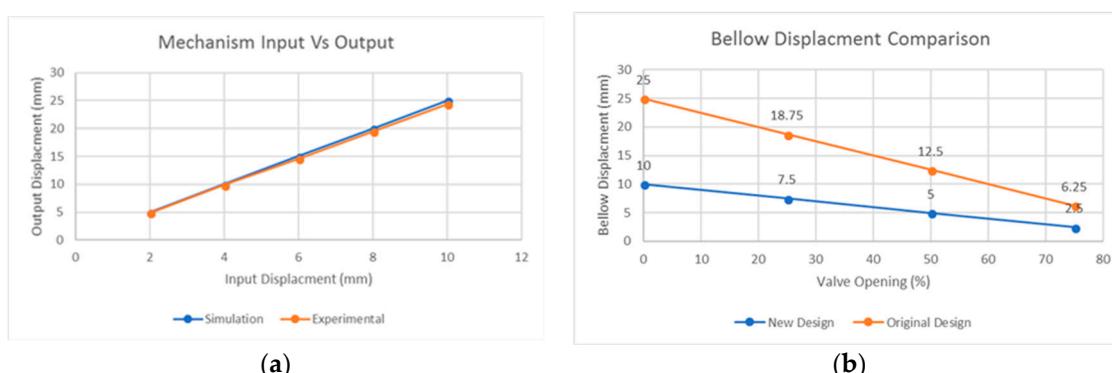


**Figure 7.** Experimental analysis setup.

### 3. Results and Discussion

This section presents the results and discussion on the novel design of a globe valve with compact geometry using an extending mechanism. In the current research, the performance of the valve design was analyzed with ANSYS and the experimental prototype for the position and force analysis of the valve mechanism was followed by the flow analysis of the valve. A comparative study of the results obtained from the simulation, experiment, and original design was done to evaluate the performance of the new valve design.

Figure 8a shows the comparison of the output displacement at the disc from the simulation and experiment. Results were similar with negligible difference. The difference in values was due to the tolerance of joints in the mechanism and surface roughness, due to which the movement of the joints was not very smooth. Figure 8b shows the comparison of the displacement required at the input to produce the required output at the disc. The input displacement required for the new design was significantly less when compared to the original design. In contrast to the conventional design where the input displacement was the same as the output due to the rigid shaft, the applied mechanism reduced the required input while maintaining the output. A decrease in the required input displacement decreased the required length of the bellow as less displacement will need less bellow length, which in turn will reduce the overall valve structure. It can be observed, with the application of the six-bar linkage, the required displacement at the input was about 2.5 times less in magnitude when compared to the required displacement in the original design. Tables 2 and 3 show the comparison of the output between the simulation, experiment, and original design.



**Figure 8.** (a) Comparison of position analysis from the simulation and experiment. (b) Input displacement comparison of the original and new design.

**Table 2.** Comparison of output displacement from simulation and experiment.

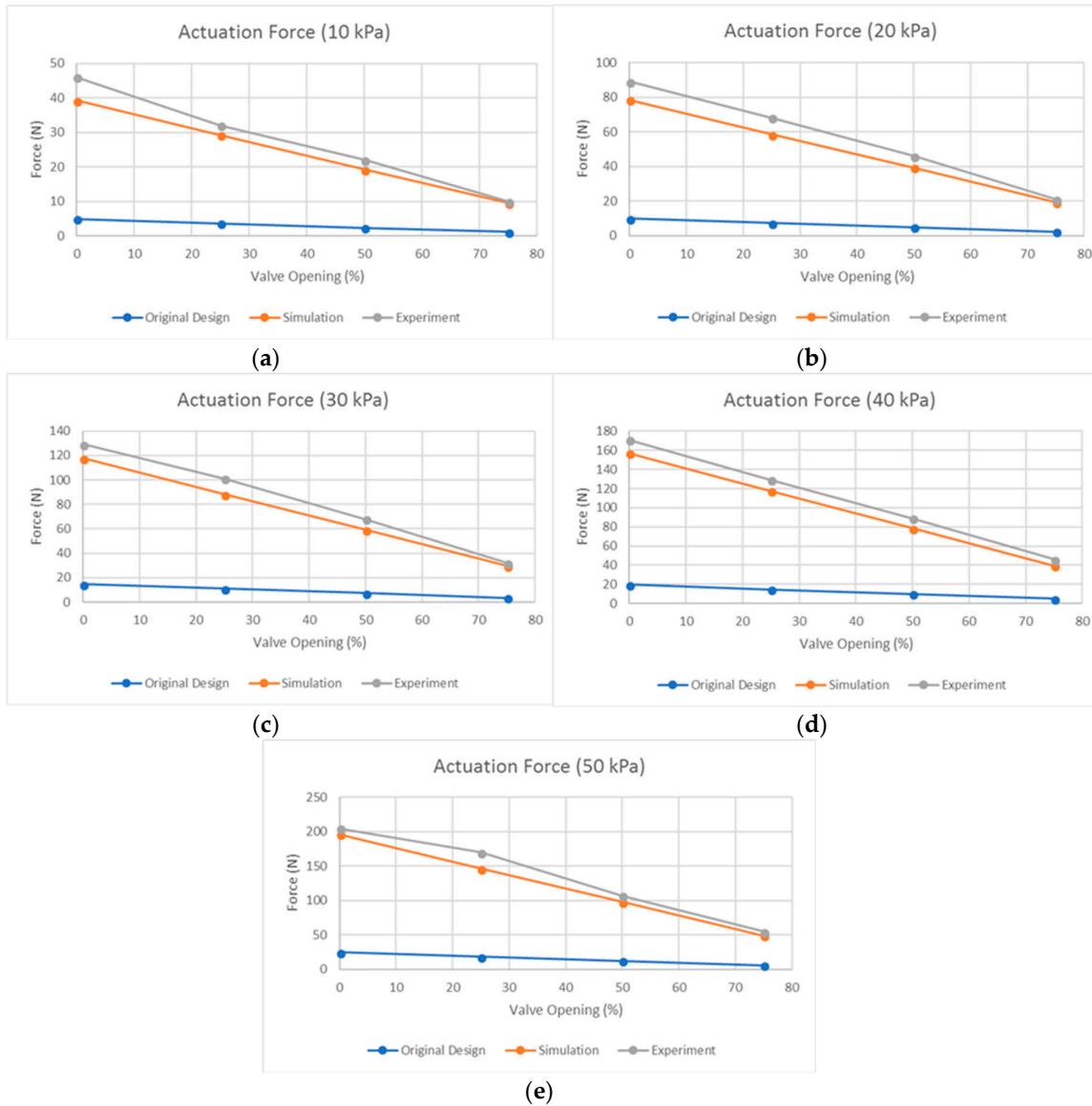
Input Displacement (mm)	Output Displacement (mm)	
	Simulation	Experiment
2.0	5.0	4.9
4.0	10.0	9.9
6.0	15.0	14.6
8.0	20.0	19.5
10.0	25.0	24.4

**Table 3.** Bellow displacement comparison of the original and new design.

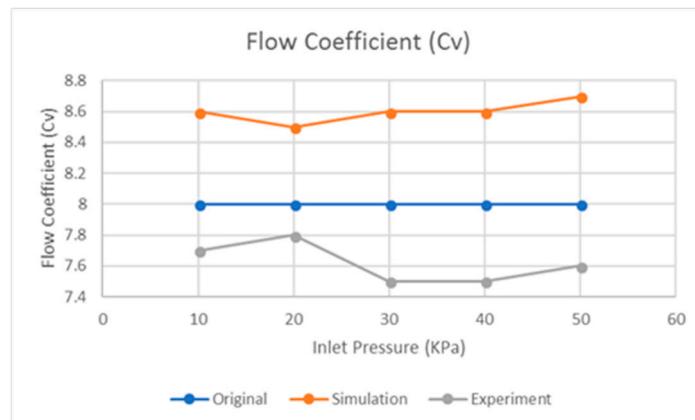
Valve Opening (%)	Bellow Displacement (mm)	
	New Design	Original Design
75	2.5	6.25
50	5.0	12.50
25	7.5	18.75
0	10.0	25.00

A comparison of the force required to operate the valve for the original, simulated, and experiment design is shown in Figure 9a–e. Figures show the comparison of the actuation force at different valve opening positions for pressure ranging from 10 to 50 kPa. As seen from the figures, the force required for the new design was significantly higher than the original design. For the original design, the force required to operate the valve was assumed to be same as the force acting on the disc due to the fluid pressure. The force required by the mechanism as obtained from the simulation was eight times more than that of the original design whereas for the experimental, the required force was up to ten times more than the original. The difference in the simulation and experiment could be explained due to the tolerance and friction in the mechanism in the joints which make the movement unsmooth. The difference between the force required for the new design and original design was due to the force distribution in the linkages of the mechanism. Force in the reciprocating shaft was assumed to be equal to the pressure acting on the disc. An equal and opposite reaction force was required at the input to operate the valve. In the current design of the valve, the disc was attached to the input handle via the reciprocating shaft. Assuming that the shaft is rigid, the reaction force produced at the output (disc) is equal to the input force applied. Therefore, the force required to operate the valve is equal and opposite to the force being applied on the disc due to the fluid pressure. The results showed that the force required to operate the valve increased with the increase in fluid pressure and also increased as the valve was closed. The original, simulation, and experiment all showed the same trend in actuation force. Table 4 shows the actuation force for the valve at different inlet pressures.

A comparison of the flow coefficient for the original, experimental, and simulated design is shown in Figure 10 at different pressure inlets. Results showed that with the application of a six-bar mechanism to the valve, there was no significant difference in the flow efficiency of the valve. The flow coefficient for the original design was taken from the manufacturer's catalogue for DN 25 globe valve. The flow coefficient obtained from the simulation was higher when compared to the original due to the frictionless assumption in the analysis whereas values from the experiment were lower than rated. This is because the surface finish of the prototype from the plastic 3D printing was lesser quality when compared to the metal finish.



**Figure 9.** Valve actuation force comparison at: (a) 10 kPa; (b) 20 kPa; (c) 30 kPa; (d) 40 kPa; (e) 50 kPa.



**Figure 10.** Flow coefficient comparison with original design.

**Table 4.** Actuation force comparison.

Inlet Pressure (kPa)	Valve Opening (%)	Actuation Force (N)		
		Original Design	Simulation	Experimental
10	75	1.20	9.6	10.0
	50	2.40	19.2	22.0
	25	3.65	29.2	32.0
	0	4.90	39.2	46.0
	75	2.40	19.2	21.0
	50	4.90	39.2	46.0
20	25	7.30	58.4	68.0
	0	9.80	78.4	89.0
	75	3.70	29.6	32.0
	50	7.40	59.2	68.0
	25	11.00	88.0	101.0
	0	14.70	117.6	129.0
30	75	4.90	39.2	46.0
	50	9.80	78.4	89.0
	25	14.70	117.6	129.0
	0	19.60	156.8	171.0
	75	6.10	48.8	55.0
	50	12.20	97.6	107.0
40	25	18.30	146.4	170.0
	0	24.50	196.0	205.0

As described in the Introduction, the problem of long bellow lengths exists in bellow valves to produce the required disc motion. Our goal was to minimize the length of the bellow required by using the mechanism synthesized to generate the same output motion at the disc. In this research, a DN 25 bellow globe valve was used. The bellow length in the valve was about 305 mm, which makes the height of the valve significantly long. To fully open and close the valve, the disc has to cover the displacement of 25 mm. Using the linkage synthesized above, a mechanism was designed for the valve that reduced the input displacement required by keeping the output constant. Reduced input will in turn reduce the length of the bellow required for the valve. For this purpose, CAD software was used to model the mechanism for opening and closing the valve.

The output link of the mechanism was attached to the disc and input link was attached to the bellow. By rotating the handle wheel, the rotary motion of the hand wheel was converted into the translatory motion of a rod by screw threads. The other end of this rod was attached to the mechanism and acted as the input link. The translatory motion produced in this rod was converted into a larger displacement at the disc through the mechanism. A bellow was attached to the valve with one end connected to the rod while the other was connected to the valve bonnet to provide sealing. The attached bellow compressed with the translatory motion of the valve while closing the valve and came back to its natural position while opening. Due to the small displacement of the input rod, the length of the bellow was significantly reduced or in this case, the length of the bellow was reduced to 50 mm if the material of the bellow was 316 L stainless steel as the displacement required to produce the desired output was only 10 mm.

Bellow valves are a potential solution for no emissions from the valve, but their long length restricts their use until necessary. In the sections above, a mechanism was synthesized and analyzed to solve the problem of the long height of the bellow valve. From the literature, the height of the bellow valve was defined by the length of the bellow. By introducing the synthesized linkage to the bellow valve, less input displacement could be converted into the required output motion. This reduced the requirement of the long bellow length, which as a result, reduced the height of the valve. As in this study, with the requirement of less input displacement, the length of the bellow was reduced from 305 mm to 50 mm. This allowed the height of the bonnet in the valve to be reduced further, here from 300 mm to 150 mm, which is a significant reduction. The bonnet height in the valve determines the

overall height of the valve, which after the application of the mechanism, made the height of the valve equal to the conventional packing sealed valves.

The dimensions for the mechanism applied in the valve is dependent on the valve size being used. As in the case here, the mechanism was applied to a DN 25 globe valve. The diameter of the bonnet in the valve was also 25 mm, which limits the length of the linkages. The length of the link must be less than 25 mm to allow for the motion of the links. To achieve the desired input and output displacement, more ternary links were added. For the different size of the valve, the length of the links and number of additional links could be selected accordingly. This will determine the height reduction of the valve and also the force propagation.

Valves are available in a variety of pressure ranges depending upon the application that they are used for. Fluid pressure through the valve determines the force required to operate the valve. In conventional valves, it is usually equal to the force exerted by the fluid pressure on the valve disc. To overcome the resistance by the fluid, a little higher force is required to open or close the valve. As discussed in the force analysis section, the applied input force is reduced, after propagation through the mechanism, at the output. To operate the valve with the applied mechanism, a lot more force will be required. As the force analysis of the test rig showed, approximately ten times more force was required to operate when compared to the conventional valve. It may not be possible to actuate a high-pressure range valve by human force, but it will not affect the use of a valve as most of the control valves in industries today are operated using electronic actuators. Required force can easily be applied by motors to operate the valve.

The application of the synthesized linkage is not limited to different size ranges of the globe valve. The mechanism can also be applied to other types of valves such as gate valves. As the mechanism is designed to operate the disc, all valves that work on a similar principle can work with the mechanism with little modifications. Using the mechanism for opening and closing the valve greatly reduces the height of the valve while maintaining the zero-emission characteristic of the valve. This design makes bellow valves more suitable and can increase their use in daily industrial applications.

#### 4. Conclusions

In this research application of a six-bar linkage to a bellow valve was analyzed in an attempt to reduce the overall height of the valve. The length of the required bellow was reduced by 50% with the application of a six-bar linkage to the control mechanism of the valve. A globe valve with a new linkage was analyzed numerically and experimentally by producing a valve prototype. From the results, it can be concluded that the synthesized linkage produced an extended output displacement when compared to the input displacement. The application of the linkage to the bellow valve significantly reduced the required bellow length, which in turn, reduced the overall height of the valve. This makes the design of the valve more compact and suitable for larger sizes of valves. Force propagation analysis of the linkage showed that less force was produced at the output when compared to the force applied at the input. The application to the valve showed, compared to the existing design, that the new design required more actuation force to operate the valve, as the extending mechanism reduced the force at the output. However, the required force was still in the range that it could be applied through electronic actuators. Application of the new mechanism to the valve had no effect on the flow efficiency of the valve. Results have shown that the flow coefficient of the valve remained unchanged. In the current research, the scope was limited to the globe valve, which was size DN 25. Additionally, the prototype was produced using plastic material for the initial testing of the new design. Future work related to this research includes the production of a functional prototype that could be used for extensive testing in the field. The mechanism can also be applied to other types and sizes of valves to study their performance compared to existing designs.

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## References

1. Ippc, E.U.; Esa, D. *Sealing Technology—BAT Guidance Notes*; European Sealing Association: Wayne, PA, USA, 2009; Volume 9.
2. Emissions Compliance. *The Hidden Cost. The Valve's Role IN Fugitive*; Emissions Compliance: Birmingham, AL, USA, 2014; Volume XX, No. 5.
3. Smith, P.; Zappe, R.W. *Valve Selection Handbook*, 5th ed.; Elsevier: Amsterdam, The Netherlands, 2004.
4. Flitney, R. *Seals and Sealing Handbook*, 6th ed.; Elsevier: Amsterdam, The Netherlands, 2014.
5. Pennock, G.R.; Kassner, D.J. Kinematic analysis of a planar eight-bar linkage: Application to a platform-type robot. *ASME J. Mech. Des.* **1992**, *114*, 87–95. [[CrossRef](#)]
6. Erdman, A.G.; Sandor, G.N.; Kota, S. *Mechanism Design: Analysis and Synthesis*; Prentice-Hall: Upper Saddle River, NJ, USA, 2001.
7. Gezgin, E.; Chang, P.; Faruk, A. Synthesis of a Watt II six-bar linkage in the design of a hand rehabilitation robot. *Mech. Mach. Theory* **2016**, *104*, 177–189. [[CrossRef](#)]
8. Batayneh, W.; Al-araidah, O.; Malkawi, S. Biomimetic Design of a Single DOF Stephenson III Leg Mechanism. *Mech. Eng. Res.* **2013**, *3*. [[CrossRef](#)]
9. Plecnik, M.; McCarthy, J.M.; Wampler, C.W. Kinematic Synthesis of a Watt I Six-Bar Linkage for Body Guidance. In *Advances in Robot Kinematics*; Springer: Cham, Switzerland, 2014; pp. 317–325.
10. Chen, F.-C. Analysis and Verification of a Watt I Six-Bar Furniture Hinge Mechanism. *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* **2005**, *219*. [[CrossRef](#)]
11. Norton, R.L. *Design of Machinery: An Introduction to the Synthesis and Analysis of Mechanisms and Machines*, 3rd ed.; McGraw-Hill: New York, NY, USA, 2003.
12. Gibson, I.; Rosen, D.; Stucker, B. *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*; Springer: Cham, Switzerland, 2014.
13. Azam, F.I.; Rani, A.M.A.; Altaf, K.; Zaharin, H.A. Additive manufacturing design of globe valve for optimized flow. *Trans. Can. Soc. Mech. Eng.* **2017**. accepted.
14. Chekurov, S.; Lantela, T. Selective Laser Melted Digital Hydraulic Valve System. *3D Print. Addit. Manuf.* **2017**, *4*, 215–221. [[CrossRef](#)]
15. Salmi, M.; Ituarte, I.F.; Chekurov, S.; Huotilainen, E. Effect of build orientation in 3D printing production for material extrusion, material jetting, binder jetting, sheet object lamination, vat photopolymerisation, and powder bed fusion. *Int. J. Collab. Enterp.* **2016**, *5*, 218–231. [[CrossRef](#)]



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