A Review of Fuzzy Logic Method Development in Hydraulic and Pneumatic Systems

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Abstract: Fuzzy logic has been developed since the 1960s. Research related to fuzzy logic application in hydraulics and pneumatics is mainly aimed at energy demand reduction and improvement in operational characteristics. This article summarizes the recent achievements in hydraulic and pneumatic fuzzy logic system design. First, the main application areas have been identified, including control and fault diagnosis. The control systems were additionally grouped according to the main objects of study, such as pumps, actuators, proportional valves, etc. Then, the results of the recent research were presented, and the main features of the designed fuzzy logic units were summarized for each group. Particular attention was paid to types of membership functions used for fuzzification and defuzzification, numbers of fuzzy sets defined for input and output signals, types of fuzzy operators, the applied inference algorithm and the defuzzification method. Based on the analysis of the listed parameters, conclusions were formulated regarding advantages, main issues and difficulties, as well as recommended directions for further development.

Keywords: fuzzy logic; fuzzy modelling; fuzzy control; fuzzification; inference; defuzzification; hydraulics; pneumatics

1. Introduction

The development of modern hydraulic and pneumatic systems is increasingly associated with the use of artificial intelligence techniques. One of these approaches is fuzzy logic, which was proposed by Lofti Zadeh in the 1960s as a generalization of classical two-valued logic. It introduced the concept of the degree of membership of an element in a set. This allowed the definition of state when a given element belongs to multiple sets at the same time. Further, the development of fuzzy operators for the sum and product of sets made it possible to formulate rules in the form of IF/THEN with both the premise and the conclusion fuzzified. It turned out that such rules can be particularly useful in constructing controllers of even complex systems with non-linear characteristics or under the influence of changing external factors. Unlike classic control algorithms such as Proportional–Integral–Derivative (PID) and its variants (e.g., Proportional–Derivative, PD), fuzzy logic allows significantly better compensation of disturbances and non-linearities. However, it is not advisable to use this technique in the case of simple, linear systems due to the greater computational complexity. The second significant area of research on the applications of fuzzy logic comprises failure analysis techniques. Properly defined fuzzy rules can map even complex dependencies between different kinds of factors, which may influence the possibility of failure.

The search for new solutions in the field of hydraulic and pneumatic control systems is associated with numerous problems and inconveniences, such as hysteresis, dead zones, and saturation. They result from the complex geometry of flow channels, characteristics of springs, movable elements as pistons, poppets and spools, as well as phenomena related to the flow of the fluid, including compressibility, dependence of parameters on the temperature, presence of hydrodynamic forces, critical velocities, turbulences or...
uneven distribution of velocity and pressure fields. Research mainly concerns extending or replacing classic control algorithms, such as PID, with fuzzy logic methods. Fuzzy logic is also used in research on risk assessment and failure detection of hydraulic and pneumatic systems. Particularly advantageous is the ability to save the knowledge base in the form of rules and use a fuzzy inferencing mechanism.

The analysis carried out as part of this work includes publications indexed in the Web of Science [1] and Scopus [2] databases. In the first step, the “fuzzy AND logic AND power AND hydraulic” and “fuzzy AND logic AND pneumatic” inquiries were made with the default TITLE–ABS–KEY source setting (title, abstract, keywords) with no time limits and no document type filtering. Figure 1 presents the obtained results up to and including 2022, summarized for Scopus and Web of Science, respectively. The chart shows that interest in the considered areas of fuzzy logic application in the study on hydraulic and pneumatic systems has significantly increased after 2005, and has remained at a similar level since then. The statistics for 2023 are not shown in the charts because they are still incomplete. However, the most recent publications are included in further analyses. Moreover, to present current trends and research directions, particular emphasis is placed on reviewing publications that appeared in the last five years.

![Figure 1. Publications on fuzzy logic summed for power hydraulic and pneumatic systems indexed by Scopus (solid) and by Web of Science (dashed).](image)

The Scopus database contains more items, and further, almost all publications from the WoS database are also indexed by it. Hence, subsequent charts summarizing the document types (Figure 2) and subject areas (Figure 3) were prepared based on the Scopus database.

![Figure 2. Document classification (Scopus): (a) hydraulics, (b) pneumatics.](image)

Among the publications on hydraulic systems, over 96% consists of articles and various types of conference materials (papers and reviews). In the field of pneumatic systems research, it is even more, over 98%. The leading role among the subject areas, concerning both hydraulic and pneumatic systems, is played by disciplines such as general Engineering (43.8% and 37.1% of publications) and Computer Science (11.6% and 29.0%, respectively).
However, in second place among hydraulics are the issues of Energy, which account for 14.1% and indicate that this direction of research is also essential and constantly developed. 

The following section is devoted to classifying research on fuzzy logic systems in terms of structure, methods and algorithms used, and practical applications in hydraulics and pneumatics, respectively. Within each of these areas, an analysis of components such as pumps, valves, and actuators will be carried out. Particular emphasis will be placed on the comparison and comparison of the fuzzy model features, such as the shapes of the membership functions, types of fuzzy operators, the construction of rule databases, inference methods, and defuzzification algorithms.

2. State-of-the-Art on Fuzzy Logic in Hydraulics and Pneumatics

The preliminary literature analysis showed that a standard modular structure of the fuzzy logic system is used in almost all works, consisting of the following blocks: fuzzification, inferencing connected with the rule database and defuzzification. The most significant differences appear in the inferencing system, in which two main development directions may be distinguished, including the Mamdani and Takagi–Sugeno methods. Moreover, there are studies concerning the constructional details of fuzzy logic systems, including fuzzified operators and membership functions. It also has been noted that similar design solutions apply to individual practical applications. Hence, in further analysis, it was decided to make a general division into hydraulic and pneumatic systems categories. Within each category, groups of publications concerning the two above-mentioned inference methods were distinguished, and then publications were grouped in terms of specific practical applications.

2.1. Fuzzy Logic in Hydraulic Systems

The main area of research on fuzzy logic applications in hydraulics is control, mainly related to pumps, turbines, valves and actuators. In addition, one can find publications on diagnosis and fault detection and combining with other technologies, such as neural networks or genetic algorithms.

2.1.1. Hydraulic Pump and Turbine Control Systems

Xu et al. [3] used a model predictive control and fuzzy logic control theory to study the optimal control of a pump-turbine unit under no-load start-up conditions at a low head area. The authors designed a novel predictive-fuzzy PID controller based on standard PID parameters and a controlled autoregressive integrated moving average model of the system. Xu also proposed a similar, adaptively fast fuzzy fractional order PID control method for a pumped storage hydro unit [4]. In each case, the designed fuzzy logic unit was used to determine the control signal for a servo-valve according to the diagram shown in Figure 4.

In turn, El-Koliel et al. [5] developed a speed controller of an electrical submersible pump using a rule-based fuzzy logic controller with a space vector pulse width modulator, while
Popescu [6] proposed a fuzzy logic unit for controlling frequency of a cooling water system consisting of centrifugal pumps.

![Figure 4](image)

**Figure 4.** Diagram of a pumped storage hydro unit fuzzy logic control system [4]; $x_{req}, x$ — required and actual rotational speed, $e$ — control error, $K_e, K_d$ — input scale factors, $u$ — control signal, $y$ — guide vane opening, $mt$ — pump-turbine torque, $mg$ — load torque.

The design of hydraulic turbine control systems is also a challenging research problem due to numerous non-linearities. A fuzzy-PID controller for a hydraulic turbine governing system with an elastic water hammer acting on a penstock was proposed by Li et al. [7]. The controller parameters were optimized by means of a novel gravitational algorithm based on Cauchy mutation and mass weighting. Chen et al. [8] also proposed a fuzzy logic controller for a hydraulic turbine; however, they used a hybrid imperialist competitive algorithm for tuning the parameters. Moreover, Yuan et al. [9] presented a novel approach to the load frequency control of a hydraulic turbine regulating system using a fuzzy sliding mode controller. The approach of developing a fuzzy logic unit that supports the operation of the hydraulic turbine speed PID controller by adjusting its parameters in real-time operation was presented by Osinski in [10]. The idea is shown in Figure 5.

![Figure 5](image)

**Figure 5.** Real-time tuning of hydraulic turbine PID controller by a fuzzy logic unit [10]; $e$ — control error, $u$ — control signal, $v_{req}, v$ — required and actual velocity, $K_p, K_i, K_d$ — adjusted PID parameters.

Additionally, Hao et al. [11] used the LabView platform to research a controller of the synchronous jack-up system of the turbine runner. The designed fuzzy-PID controller allowed fast stabilization of the controlled parameter with a slight overshoot. In turn, Liang et al. [12] built a novel mathematical model of a Francis turbine in Matlab and proposed a fuzzy logic controller, which reduced the chattering effect and guaranteed significantly better performance than a commonly used PID controller, while Mushiri et al. [13] used the same environment to design a fuzzy-PID controller of the speed governing system of 150 MW Francis turbines at a power station. Although most studies use Mamdani-type fuzzy inference, some models utilize the Takagi–Sugeno (T-S) method. Ma and Wang [14] designed a fuzzy controller for a hydraulic turbine governing system with an elastic water hammer. The authors built a frequency-distributed model and proposed a disturbance-observer-based T-S control method to improve the anti-interference control performance. In a subsequent work [15], Ma et al. proposed a fuzzy logic controller of the hydraulic turbine governing system based on the T-S fuzzy finite-time H-infinity method. The main features of fuzzy logic units used for pump and turbine control are summarized in Table 1.
Table 1. Specification of fuzzy logic units for hydraulic pump and turbine control.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Controlled System</th>
<th>Input Params</th>
<th>No. of Inputs</th>
<th>Input fuzz.sets</th>
<th>Input Function</th>
<th>No. of Outputs</th>
<th>Output fuzz.sets</th>
<th>Output Function</th>
<th>No. of Rules</th>
<th>Fuzzy Operators</th>
<th>Defuz. Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>[3]</td>
<td>Pump-turb. unit</td>
<td>$e,de/dt$</td>
<td>2</td>
<td>7, 7</td>
<td>triang</td>
<td>1</td>
<td>7</td>
<td>triang</td>
<td>49 (7 × 7)</td>
<td>min-max</td>
<td>WAv</td>
</tr>
<tr>
<td>[4]</td>
<td>Pumped storage unit</td>
<td>$e,d^ne/d^nt$</td>
<td>2</td>
<td>7, 7</td>
<td>triang</td>
<td>1</td>
<td>7</td>
<td>triang</td>
<td>49 (7 × 7)</td>
<td>min-max</td>
<td>CoG</td>
</tr>
<tr>
<td>[5]</td>
<td>Submersible pump</td>
<td>$e,de/dt$</td>
<td>2</td>
<td>7, 7</td>
<td>Gauss</td>
<td>1</td>
<td>7</td>
<td>triang</td>
<td>49 (7 × 7)</td>
<td>no data</td>
<td>no data</td>
</tr>
<tr>
<td>[6]</td>
<td>Cooling water sys.</td>
<td>$H_1$ (head)</td>
<td>1</td>
<td>4</td>
<td>triang</td>
<td>1</td>
<td>5</td>
<td>triang</td>
<td>4</td>
<td>no data</td>
<td>no data</td>
</tr>
<tr>
<td>[7]</td>
<td>Hydraulic turbine</td>
<td>$e,de/dt$</td>
<td>2</td>
<td>7, 7</td>
<td>triang + Gauss</td>
<td>3</td>
<td>7</td>
<td>Gauss</td>
<td>147 (3 × 49)</td>
<td>no data</td>
<td>no data</td>
</tr>
<tr>
<td>[8]</td>
<td>Hydropower station</td>
<td>$s(e, de)$</td>
<td>1</td>
<td>5</td>
<td>triang + Gauss</td>
<td>1</td>
<td>5</td>
<td>triang</td>
<td>5</td>
<td>min-max</td>
<td>no data</td>
</tr>
<tr>
<td>[9]</td>
<td>Hydraulic turbine</td>
<td>$s(e, de)$</td>
<td>1</td>
<td>3</td>
<td>triang</td>
<td>1</td>
<td>3</td>
<td>triang</td>
<td>3</td>
<td>no data</td>
<td>no data</td>
</tr>
<tr>
<td>[10]</td>
<td>Hydraulic power system</td>
<td>$e,de/dt$</td>
<td>2</td>
<td>5, 5</td>
<td>triang</td>
<td>3</td>
<td>5</td>
<td>triang</td>
<td>75 (3 × 25)</td>
<td>no data</td>
<td>Centroid</td>
</tr>
<tr>
<td>[11]</td>
<td>Turbine runner</td>
<td>$e,de/dt$</td>
<td>2</td>
<td>7, 7</td>
<td>no data</td>
<td>3</td>
<td>7</td>
<td>no data</td>
<td>49 (7 × 7)</td>
<td>no data</td>
<td>unknown</td>
</tr>
<tr>
<td>[12]</td>
<td>Hydraulic turbine</td>
<td>$s(e, de)$</td>
<td>1</td>
<td>3</td>
<td>triang</td>
<td>1</td>
<td>3</td>
<td>triang</td>
<td>3</td>
<td>no data</td>
<td>CAv</td>
</tr>
</tbody>
</table>

It can be noted that almost all studies, except [11], are carried out in Matlab, with additional modules such as Simulink and Fuzzy Logic Toolbox. The developed systems usually have two inputs in the form of an error and its derivative. There is usually one output in the case of stand-alone fuzzy logic controllers and three outputs in fuzzy units, which are designed to adjust PID coefficients. Triangular or Gauss membership functions are commonly used to create fuzzy sets of both input and output variables. Usually, the Mamdani inferencing system, with the help of IF/THEN rules and simple min-max operators, is implemented; however, Refs. [14,15] use the T-S method. Various methods are used for defuzzification of the output signal; however, sometimes, the authors do not provide detailed information. The main difficulties reported by the authors are related to the problems with the proper rule formulation, which is usually based on expert knowledge and lack of automatic adjustment methods.

2.1.2. Hydraulic Flow Control Valves and Servo Valves

Fuzzy logic systems are often used to control actuators in positioning and motion synchronization systems, including autonomous vehicles, by means of proportional pressure valves, proportional flow control valves or servo valves. Research on force control was conducted by Li [16] in relation to a single-rod electro-hydraulic actuator and by Chen [17] on the example of a deep-sea hydraulic manipulator. In both cases, a fuzzy logic system was used to adjust the parameters in real-time during the operation, which significantly improved control performance, including maintaining forces in an acceptable range and expanding the operational capabilities of the tested systems. A large number of research works on actuator positioning include the use of fuzzy logic systems to control servo valves. Du et al. [18] designed a fuzzy-PD control system based on a fractional-order PID controller and a fuzzy logic unit for trajectory-tracking of an electro-hydraulic rotary actuator. Like the previously mentioned research, the fuzzy logic unit was designed to adjust the PID parameters according to time-variant working conditions. A complex fuzzy-logic-based motion synchronization hydraulic system for large civil aircraft was proposed by Ur Rechman et al. [19]. The proposed strategy includes two fuzzy-logic-based
units for controlling the position and the force, respectively. In turn, Lu et al. [20] designed an adaptive fuzzy-PID valve lift controller for an internal combustion engine. Moreover, Guo et al. [21] focused on a flexible structured fuzzy logic controller for a large wind turbine hydraulic variable pitch system. Guo used a set of three flexible-structure fuzzy adaptive units to adjust the signals of the P-type controllers in the blade pitch angle control using hydraulic servo systems. Jin et al. [22] designed a control strategy for a transplanting manipulator on the example of displacement tracking of a hydraulic seedling picking-up system. Tho et al. [23] and Nguyen et al. [24] made two different proposals for adaptive sliding-mode fuzzy controllers for electro-hydraulic servo systems. Tho used a virtual prototyping technique. Nguyen separated the controller into two control loops related to mechanical and hydraulic dynamics, which allowed them to reduce the controller’s order and increase its robustness. Similarly, Li et al. [25] analysed an adaptive fuzzy controller for an electro-hydraulic servo system. Moreover, Truong et al. [26] designed a back-stepping sliding mode fuzzy logic system, including two controllers for a manipulator and an actuator, respectively. A typical method of placing a fuzzy controller in a hydraulic position-tracking system is shown in Figure 6.

![Figure 6. Fuzzy logic controller in a hydraulic position-tracking system [22]; e, e_c — control error and its change, E, EC, KP, KI, KD — fuzzy values, K_p, K_i, K_d — determined PID parameters, u — control signal, I — electromagnet current, Q — servo valve flow rate, y, y_r — actual and required position.](image)

One can also find publications on constructing fuzzy-PID systems for non-linear positioning systems using proportional flow control valves. Wrat et al. [27] focused on the energy efficiency of a linear actuator applied in heavy earth movement equipment. In turn, Bao et al. [28] developed a motion control system for a truck-mounted concrete pump boom. Bao used cartridge flow control valves instead of traditional proportional directional spool valves and a fuzzy-logic-based active disturbance rejection control algorithm, which significantly improved the stability and rapidity of the valve’s operation. Moreover, Tatoglu et al. [29] designed a single-stage valve-actuated robotic arm, while Tony Thomas et al. [30] modelled and simulated an electro-hydraulic system with a double-acting cylinder and a proportional flow control valve. In both approaches, the Mamdani-type fuzzy logic controllers were applied.

Recently, there has been an increasing number of works on fuzzy logic systems for vehicles, including autonomous and hybrid ones, as well as heavy-duty machines. These systems are usually based on flow control via proportional valves or servo valves. Applications of fuzzy logic here may include energy savings, movement and performing operational tasks. Li et al. [31] proposed an open-loop fuzzy controller for the mechanical-electro–hydraulic power coupling system of electric vehicles (Figure 7). Application of a rule-based fuzzy logic energy management strategy allowed the battery power consumption to be reduced by 14.7%.
Figure 7. Fuzzy control principle of an electric vehicle power coupling system [31]; acc—accelerator signal, \(v\)—velocity, \(T_d\)—total demanded torque, \(K\)—motor torque to the demanded torque ratio.

In turn, Hanafi et al. made an attempt to minimize tracking errors of the bucket tip position for an autonomous excavation [32]. The proposed collaboration of PID and fuzzy controllers allowed compensation for contour errors and accurate position control. In turn, Truong in [33] focused on the fuzzified configuration of hybrid power sources for hydraulic excavators. The proposed energy management strategy using a new mapping fuzzy logic control for appropriate power distribution increased energetic efficiency up to 47% compared to the standard solutions. Delavarpour et al. [34] proposed a novel fuzzy-logic-based adaptive steering algorithm for a tractor-cart vehicle used in agriculture. A hydraulic drive design for the cart considered two main control aims, including following the required path and minimizing the possibility of damaging plants. Moreover, Han et al. [35] studied steering techniques of hydraulic-driven tracked vehicles, while Yang et al. [36] focused on fuzzy control of dual hydraulic pumps/motor systems of electric sport utility vehicles. A number of publications concern flow control, energy management and power optimization. Yang et al. [37] designed and optimized a similar system combining an electric motor and a piston pump, achieving an even better reduction in power consumption, up to 21.17%. Eckert carried out a series of studies on fuzzy logic applications in hybrid vehicle power distribution systems to minimize energy demands and decrease emissions [38,39].

The parameters of fuzzy logic units designed for hydraulic control systems based on proportional flow control valves and servo valves are listed in Table 2.

Table 2. Specification of fuzzy logic units for proportional flow control valves and servo valves.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Controlled System</th>
<th>Input Params</th>
<th>No. of Inputs</th>
<th>Input fuz.sets</th>
<th>Input Function</th>
<th>No. of Outputs</th>
<th>Output fuz.sets</th>
<th>Output Function</th>
<th>No. of Rules</th>
<th>Fuzzy Operators</th>
<th>Defuz. Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>[16]</td>
<td>Electro-hyd. actuator</td>
<td>(v_c/F_c)</td>
<td>2</td>
<td>5, 5</td>
<td>triang</td>
<td>2</td>
<td>7</td>
<td>triang</td>
<td>50</td>
<td>(2 × 25)</td>
<td>CoG</td>
</tr>
<tr>
<td>[17]</td>
<td>Deep-Sea hyd. manip.</td>
<td>(\dot{e}/dt)</td>
<td>2</td>
<td>7, 7</td>
<td>Gauss</td>
<td>2</td>
<td>7</td>
<td>triang</td>
<td>98</td>
<td>(2 × 49)</td>
<td>CoA</td>
</tr>
<tr>
<td>[18]</td>
<td>Electro-hyd. rotary actuatl.</td>
<td>(\dot{e}/e)</td>
<td>2</td>
<td>4, 4</td>
<td>triang</td>
<td>3</td>
<td>4</td>
<td>triang</td>
<td>48</td>
<td>(3 × 16)</td>
<td>Centroid</td>
</tr>
<tr>
<td>[19]</td>
<td>Hybrid actuation sys.</td>
<td>(\dot{e}<em>p/\dot{e}</em>{f}/dt)</td>
<td>2</td>
<td>5, 5</td>
<td>triang</td>
<td>1</td>
<td>5</td>
<td>triang</td>
<td>25</td>
<td>(5 × 5)</td>
<td>no data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(e_f/\dot{e}_{f}/dt)</td>
<td>2</td>
<td>5, 5</td>
<td>triang</td>
<td>2</td>
<td>5</td>
<td>triang</td>
<td>50</td>
<td>(2 × 25)</td>
<td>no data</td>
</tr>
<tr>
<td>[21]</td>
<td>Wind turb. pitch control</td>
<td>(\Delta e_i)</td>
<td>2</td>
<td>13, 13</td>
<td>no data</td>
<td>1</td>
<td>15</td>
<td>no data</td>
<td>min-max</td>
<td>CoA</td>
<td>MoM</td>
</tr>
<tr>
<td>[22]</td>
<td>Hyd. transpl. robot</td>
<td>(\dot{e}/dt)</td>
<td>2</td>
<td>7, 7</td>
<td>triang</td>
<td>3</td>
<td>7</td>
<td>triang</td>
<td>147</td>
<td>(3 × 49)</td>
<td>no data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(s(e, \dot{e}, \ddot{e}))</td>
<td>1</td>
<td>7</td>
<td>triang</td>
<td>1</td>
<td>7</td>
<td>singl. set</td>
<td>7</td>
<td>not appl.</td>
<td>CAv</td>
</tr>
</tbody>
</table>
This section summarizes the studies on fuzzy logic controllers proposed for proportional flow control valves and servo valves. These types of controllers are usually used in electro-hydraulic positioning systems, manipulators and vehicles. The inputs are usually control errors and their derivatives, calculated based on the signals from displacement, rotation angle, force or torque transducers. All the presented fuzzy logic systems use the Mamdani-type inference methodology. Except for [23], they have two input signals, while the number of output signals differs, ranging from one to three. Hence, there are significant differences in the number of rules, from 7 to 147. The simplest triangular or Gauss membership functions and min-max fuzzy operators are usually used. The range of defuzzification algorithms used includes Center of Gravity, Center of Area, Centroid, Medium of Maxima, and Center-average. Regarding modelling and simulation systems, most of the works used Matlab with the Simulink module. Additionally, the Visual Studio programming environment was used in [17], AMESim in [18,23], and LabView in [27]. It is worth noting that the designed fuzzy logic units for autonomous vehicles have relatively more inputs (from 2 up to even 4). This implies a larger number of fuzzy rules and thus bigger rule database. The membership functions are also diverse; in addition to triangular and Gaussian, the trapezoidal and combined functions also appear.

It arises from the mentioned publications that fuzzy controllers with two inputs and the Mamdani inference method are most commonly designed for proportional and servo valves. However, there are still some discrepancies regarding the number of outputs and, therefore, the number of rules. Databases containing 25 to 147 rules are used to solve...
problems of comparable complexity. Moreover, there are also no clear rules regarding the optimal number of fuzzy sets for individual input and output parameters, which range from 2 to even 15.

2.1.3. Fuzzy Risk Assessment and Fault Detection of Hydraulic Systems

Risk assessment and fault detection in hydraulic systems can also be realised by means of fuzzy logic methods. Karghar et al. [40] used the fuzzy fault tree analysis technique to assess the risk of a crane overturning in the asymmetric tandem lift operation. The required knowledge base in the form of 53 events was collected from the literature review, expert experience and previous incidents and allowed the enhancement of reliability and sustainability of the lifting process. Similarly, Ghini and Vacca analysed the remaining useful life of a truck-mounted hydraulic crane [41]. They proposed a neural network designed with a fuzzy logic system to estimate the percentage of life already spent by hydraulic components such as a pump or valves. Liu [42] also utilised a Takagi–Sugeno-based fuzzy fault tree for diagnosing the hydraulic power system of a coal mine tunnel drilling. In turn, Yu et al. in [43] utilised the fuzzy probabilistic Petri net method to assess the risk of the submarine pipeline leakage failure, significantly improving the pipeline operation’s safety. Moreover, Filo et al. [44] examined a fuzzy logic interface for the risk analysis of a turbocharger with the help of a sheet-based Failure Mode and Effects Analysis (FMEA) method. Furthermore, Jiang et al. [45] combined the fuzzy adaptive position controller of an electro-hydraulic system with the fuzzy fault-tolerant control of the actuators. In contrast, Li et al. [46] made an attempt to improve the reliability of hydraulic automated guided vehicles by means of a fuzzy logic condition monitoring system created using type-2 functions.

The main problems pointed out by the authors mainly concern the large number of parameters taken into account in risk assessment and fault detection systems, which leads to a significant expansion of the rule base and difficulties in considering all the relationships between the individual parameters. The second inconvenience is related to the considerable differences in the parameter types, which can be logical, from a finite set, from a continuous range, etc.

2.1.4. Fuzzy Logic with Other AI Techniques in Hydraulics

Fuzzy logic applied in hydraulic control systems may be combined with AI techniques such as genetic algorithms (GA), Particle Swarm Optimization (PSO) and neural networks (ANN). A neuro-fuzzy control system for a hydraulic–electric hybrid vehicle was proposed by Kamal and Adouane [47] in order to minimise energy consumption. Gaspar et al. [48] utilised neuro-fuzzy modelling for the variable-displacement oil-hydraulic pumps’ efficiency in a wave energy converter combined with the fuzzy control pressure control system. In turn, Zhang et al. [49] optimised a pump-as-turbine unit in storage mode. The optimisation strategy combined fuzzy logic with genetic algorithms and allowed an increase in efficiency by 3.8% and an effective reduction in radial force by over 37%. Similarly, Mostafa et al. [50] optimised parameters of a hydraulic energy storage system. Moreover, Doan et al. [51] proposed a fuzzy-PID-based load frequency control (LFC) strategy for a power system hydraulic turbine applying Particle Swarm Optimization.

The outcomes of publications combining fuzzy logic with other AI techniques indicate that such a mixture has great potential, especially in solving optimization problems. There is a lot of space for developing research on using technologies such as PSO or GA for the automatic adjustment of fuzzy logic system parameters.

2.2. Fuzzy Logic in Pneumatic Systems

Fuzzy logic in pneumatic systems is the most commonly used for control purposes via on/off valves, proportional pressure valves or servo valves for various electro-pneumatic systems. Tagosoglu formulated a set of practical design rules for fuzzy logic pneumatic control systems [52], considering the most common issues, such as medium compressibility,
friction, stick-slip phenomenon, etc. However, there are areas of particular interest, including manipulator design, artificial muscle design, positioning, and active suspension control. There are also studies on risk analysis, fault detection and combined neuro-fuzzy systems.

2.2.1. Pneumatic Control Systems with on/off Valves

Lin et al. [53] designed a precise force-tracking fuzzy controller of a pneumatic actuator using four on/off valves and a pulse width modulation (PWM) technique. It is worth noting that a stand-alone fuzzy logic system was employed without the use of a PID algorithm (Figure 8).

![Figure 8. Fuzzy logic controller in an electro-pneumatic system [53], $F_{c0}, F_c$—required and actual force, $F_x$—normalized volume flow (%).](image)

Moreover, solutions for position control of electro-pneumatic systems based on high-speed on/off valves and the Pulse-Width-Modulation (PWM) technique were provided by Du et al. [54] in a cylinder position control via a pneumatic digital bridge circuit and Abdul-Lateef et al. [55] related to the design of a low-cost electro-pneumatic module. Key parameters of the presented fuzzy logic pneumatic control systems based on the on/off valves are shown in Table 3.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Controlled System</th>
<th>Input Params</th>
<th>No. of Inputs</th>
<th>Input fuzz.sets</th>
<th>Input Function</th>
<th>No. of Outputs</th>
<th>Output fuzz.sets</th>
<th>Output Function</th>
<th>No. of Rules</th>
<th>Fuzzy Operators</th>
<th>Defuz. Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>[53]</td>
<td>El.-pneum. actuator $e$, $\dot{e}$</td>
<td>2</td>
<td>7, 7</td>
<td>triang trapez</td>
<td>1</td>
<td>6</td>
<td>triang</td>
<td>49 (7 × 7)</td>
<td>min-max</td>
<td>CoG</td>
<td></td>
</tr>
<tr>
<td>[54]</td>
<td>$4 \times$ solen. on/off valve $e$, $\dot{e}$</td>
<td>2</td>
<td>5, 5</td>
<td>triang</td>
<td>3</td>
<td>5, 5, 5</td>
<td>triang</td>
<td>25 (5 × 5) 3 out</td>
<td>no data</td>
<td>CoG (PWM)</td>
<td></td>
</tr>
<tr>
<td>[55]</td>
<td>$4 \times$ solen. on/off valve $e$, $\dot{e}$</td>
<td>2</td>
<td>7, 7</td>
<td>triang</td>
<td>1</td>
<td>7</td>
<td>triang</td>
<td>49 (7 × 7)</td>
<td>no data</td>
<td>no data (PWM)</td>
<td></td>
</tr>
</tbody>
</table>

Electro-pneumatic fuzzy logic control systems based on on/off valves use triangular membership functions with two inputs and one or three outputs. Both input and output signals are divided into 5 to 7 fuzzy sets. The Mamdani inferencing system and Centre of Gravity defuzzification method are used.

The results of research on pneumatic systems with on/off valves show that fuzzy logic allows for expanding the operational capabilities of these types of not-expensive systems; however, the use of a more complex PWM control technique is required.

2.2.2. Pneumatic Proportional Valves and Servo Valves

Proportional or servo valves are the most commonly used components of fuzzy logic pneumatic control systems. Lisowski and Filo [56] designed a fuzzy logic controller for a pneumatic cushion-based transport platform with four proportional valves. The work aimed at reducing energy consumption by minimizing the operating pressure. The proposed control system is shown in Figure 9. Subsequently, Mushiri et al. [57] developed a fuzzy logic controller for keeping the pressure and temperature of a bottle washing machine within the required range, and Gilian et al. [58] presented an application of fuzzy logic in
pneumatic cylinder expansion timing. Several studies utilize Takagi-Sugeno inferencing. Misra et al., in [59,60], presented a novel fuzzy-PI T-S-based controller for reducing stiction in pneumatic control valves. Chen et al. designed a set of fuzzy T-S controllers of pneumatic flexible joints, including an interval type-2 disturbance observer-based solution [61] and a data-driven predictive system [62]. Parameters of the presented pneumatic fuzzy logic controllers are shown in Table 4.

Figure 9. Fuzzy logic controller for a transport platform on pneumatic cushions [56], $p_i$—pressure, $Y_i, Y_{req,i}$—actual and required cushion lifting height, $u_i$—control signal.

Table 4. Specification of pneumatic fuzzy logic pressure control systems.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Controlled System</th>
<th>Input Params</th>
<th>No. of Inputs</th>
<th>No. of Inputs</th>
<th>Input fuzz.sets</th>
<th>Input Function</th>
<th>No. of Outputs</th>
<th>Output fuzz.sets</th>
<th>Output Function</th>
<th>No. of Rules</th>
<th>Fuzzy Operators</th>
<th>Defuz. Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>[56]</td>
<td>Pneum.cush. platform</td>
<td>$c_i, \dot{c}_i$ $i = 1 \ldots 4$</td>
<td>2 each</td>
<td>3, 3 each</td>
<td>Gauss</td>
<td>1 each</td>
<td>3 each</td>
<td>Gauss</td>
<td>9 each</td>
<td>min-max</td>
<td>prod-por</td>
<td>CoG</td>
</tr>
<tr>
<td>[58]</td>
<td>Pneumatic vehicle</td>
<td>$p, v$</td>
<td>2</td>
<td>5, 3</td>
<td>Gauss</td>
<td>1</td>
<td>5</td>
<td>trapez</td>
<td>15</td>
<td>no data</td>
<td>no data</td>
<td></td>
</tr>
<tr>
<td>[59]</td>
<td>Pneum.flow system</td>
<td>$\dot{e}$ $e$</td>
<td>2</td>
<td>2, 2</td>
<td>Gauss</td>
<td>1</td>
<td>no data</td>
<td>Gauss</td>
<td>4</td>
<td>(T-S)</td>
<td>no data</td>
<td>T-norm</td>
</tr>
<tr>
<td>[60]</td>
<td>Pneumatic joint</td>
<td>$\dot{e}$ $e$</td>
<td>2</td>
<td>5, 5</td>
<td>Gauss Type-2</td>
<td>1</td>
<td>no data</td>
<td>Gauss Type-2</td>
<td>3</td>
<td>(T-S)</td>
<td>no data</td>
<td>no data</td>
</tr>
</tbody>
</table>

Pneumatic suspension is also an example of an object in which fuzzy logic pressure control may be used since it has strongly non-linear properties and, thus, is difficult to control through standard methods. A fuzzy-PD controller for a bellows cylinder in the active air suspension system was proposed by Woś et al. [63]. The controller significantly limited the acceleration to which the operator was subject. In turn, Ho et al. conducted a series of studies on various aspects of active air suspension control using fuzzy logic. Ho consecutively published the results of their research on the design of an adaptive observer-based fuzzy controller with displacement constraints [64], on similar research with considered actuator failures [65], and on a suspension with the unknown death zone [66].

Fuzzy logic is also used in pneumatic artificial muscle control systems. These solutions can be treated as a particular type of positioning and trajectory control systems. The technique of sliding mode fuzzy control with uncertainties and external disturbances is often used, including studies by Van Kien et al. [67], Chiang and Chen [68], Nguyen et al. [69], Anh and Van Kien [70], as well as Duong et al. [71]. Additionally, Van Kien carried out research on a two-degree-of-freedom pneumatic artificial muscle system [72] with the help of a complex multilayer Takagi-Sugeno fuzzy model and a differential evolution algorithm. Moreover, Robinson et al. [73] designed a fuzzy controller for the artificial pneumatic muscles of a heavy-lift manipulator, Al-Mosawi et al. [74] proposed an adaptive parallel fuzzy-PI controller for an analogous system, Dan et al. [75] designed a fuzzy indirect
adaptive controller for a pneumatic muscle-driven exoskeleton, while Chen et al. [76] presented a disturbance-observer-based Takagi–Sugeno fuzzy controller. Parameters of fuzzy logic controllers designed for pneumatic artificial muscles are summarized in Table 5. It is worth noting that a relatively large number of sliding mode fuzzy controllers with a single function-type input signal implement the Takagi–Sugeno inference.

Table 5. Specification of fuzzy logic units in pneumatic artificial muscle control.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Pneumatic Control el.</th>
<th>Input Params</th>
<th>No. of Inputs</th>
<th>Input fuz.sets</th>
<th>Input Function</th>
<th>No. of Outputs</th>
<th>Output fuz.sets</th>
<th>Output Function</th>
<th>No. of Rules</th>
<th>Inference System</th>
<th>Defuz. Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>[67]</td>
<td>El.–pneum. regulator</td>
<td>$s(\epsilon_m)$</td>
<td>1</td>
<td>3</td>
<td>triang</td>
<td>1</td>
<td>3</td>
<td>no data</td>
<td>3</td>
<td>T-S funct.</td>
<td></td>
</tr>
<tr>
<td>[68]</td>
<td>Proport. valve</td>
<td>$s(\epsilon, \dot{\epsilon})$</td>
<td>1</td>
<td>9</td>
<td>triang</td>
<td>1</td>
<td>9</td>
<td>singlet. set</td>
<td>9</td>
<td>Mamdani</td>
<td>CAv</td>
</tr>
<tr>
<td>[69]</td>
<td>Proport. valve</td>
<td>$s(\epsilon, \dot{\epsilon})$</td>
<td>1</td>
<td>7</td>
<td>triang</td>
<td>1</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>Mamdani</td>
<td>CAv</td>
</tr>
<tr>
<td>[70]</td>
<td>Proport. valve</td>
<td>$s(\epsilon, \epsilon_{k-1})$</td>
<td>1</td>
<td>5</td>
<td>Gauss</td>
<td>1</td>
<td>5</td>
<td>no data</td>
<td>5</td>
<td>T-S</td>
<td>WAu</td>
</tr>
<tr>
<td>[73]</td>
<td>Proport. valve</td>
<td>$\dot{\epsilon}$</td>
<td>2</td>
<td>7, 7</td>
<td>triang</td>
<td>1</td>
<td>7</td>
<td>triang</td>
<td>49 (7 x 7)</td>
<td>Mamdani</td>
<td>CoG</td>
</tr>
<tr>
<td>[74]</td>
<td>Prop. press. valve</td>
<td>$\epsilon$</td>
<td>2</td>
<td>3, 3</td>
<td>Gauss</td>
<td>1</td>
<td>3</td>
<td>triang</td>
<td>9 (3 x 3)</td>
<td>Mamdani</td>
<td>CoG</td>
</tr>
<tr>
<td>[75]</td>
<td>Proport. valve</td>
<td>$\delta u$</td>
<td>2</td>
<td>3, 5</td>
<td>Gauss</td>
<td>1</td>
<td>5</td>
<td>triang</td>
<td>15 (3 x 5)</td>
<td>Mamdani</td>
<td>Centroid</td>
</tr>
<tr>
<td>[76]</td>
<td>Electromag. valve</td>
<td>$f(x_1, x_2)$</td>
<td>1</td>
<td>3</td>
<td>Gauss</td>
<td>1</td>
<td>3</td>
<td>no data</td>
<td>3</td>
<td>T-S funct.</td>
<td></td>
</tr>
</tbody>
</table>

The design of positioning techniques plays a significant role in fuzzy logic pneumatic control systems. However, fuzzy logic may be implemented in several different ways. The first possibility is a standalone fuzzy controller generating the output signal based on the control error and its derivative. This attempt was made by Nazari and Surgenor [77], Li et al. [25], Khaziew et al. [78] as well as Šitum and Čorić [79]. It is worth emphasizing that Čorić used an innovative inference method in their system. First, they defined output sets in the form of moving singletons. Next, instead of the conventional, rule-based fuzzy inference process, they used an analytic procedure for calculating the positions of the output sets using the sum-prod composition operator. Finally, the crisp output value was calculated as the average value of all output sets. Moreover, Azahar et al. [80] proposed a similar solution of a self-tuning fuzzy system except using a sliding control strategy to define the controller’s input signal.

The second group includes fuzzy-PD and fuzzy-PID systems, where the fuzzy controller is used to modify the coefficients of the primary PID controller, which controls the position of the actuator via electromagnetic valves. Proposals for such systems were presented by Azahar et al. [81,82], Tagosoglu et al. [83,84], Gao et al. [85], as well as Irawan and Azahar [86]. Furthermore, Hassan et al. [87] designed a similar system except using type-2 membership functions in the fuzzy controller. Parameters of fuzzy logic controllers applied in pneumatic positioning systems are presented in Table 6.
In pneumatic fuzzy positioning systems, fuzzy-PID controllers are used quite often. A typical fuzzy unit has two inputs in the form of control error and its derivative and three outputs since the main aim is to adjust the \((K_p, K_i, K_d)\) parameters of the PID controller in real time during the operation.

To summarize, fuzzy logic controllers are convenient for pneumatic systems with proportional pressure valves or servo valves due to the numerous non-linearities and complexity of the airflow process. A large variety of such systems have already been designed and tested experimentally, achieving promising results. The main issues are related to the necessity of arbitrary adoption of the number of fuzzy sets and rule formulation based on expert knowledge due to the lack of automatic algorithms. This constitutes one of the leading research directions for the near future.

2.2.3. Fuzzy Diagnosis and Fault Detection of Pneumatic Systems

Apart from control, fuzzy logic is also used for risk assessment and fault detection in pneumatic systems. Unlike a controller, this kind of system can take into account numerous parameters of various types in the inferencing process, which results in greater complexity and intricacy of decision-making processes. Navada and Venkata [88] made an attempt to detect and diagnose two pneumatic actuator flaws, including a stem displacement fault and an insufficient supply pressure defect. The fuzzy-based inferencing allowed the identification of an insufficient supply pressure within 1–2 s and a stem displacement fault within 3–6 s. Ali and Frimpong in [89] designed a system for real-time monitoring and predicting the performance of hydro-pneumatic suspension struts in large dump trucks. The created system incorporates Artificial Neural Networks, the Mamdani Fuzzy Logic Model and a Hybrid Neural Fuzzy Interference to allow the operator performance monitoring as well as the proper maintenance and replacement scheduling. In turn, Nicolau [90] used the fuzzy logic approach for the online predictive diagnosis of an oleo-pneumatic mechanism (MOP) of the oil-based high-voltage circuit breaker. Nicolau defined fuzzy rules to estimate the functioning state and designed several fuzzy systems for predictive diagnosis. The conducted tests proved the ability to detect the MOP fault tendencies early and efficiently. Parameters of the created fuzzy logic systems are shown in Table 7.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Pneumatic Control el.</th>
<th>Input Params</th>
<th>No. of Inputs</th>
<th>Input fuzz.sets</th>
<th>Input Function</th>
<th>No. of Outputs</th>
<th>Output fuzz.sets</th>
<th>Output Function</th>
<th>No. of Rules</th>
<th>Fuzzy Operators</th>
<th>Defuz. Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>[77]</td>
<td>press.flow cont.valve</td>
<td>(e / \dot{e})</td>
<td>2</td>
<td>7, 7</td>
<td>triang</td>
<td>1</td>
<td>13</td>
<td>singlet. set</td>
<td>49 (7 \times 7)</td>
<td>prod-max</td>
<td>CAv</td>
</tr>
<tr>
<td>[79]</td>
<td>proport. valve</td>
<td>(x_1 / x_2)</td>
<td>2</td>
<td>10, 10</td>
<td>Gauss</td>
<td>1</td>
<td>20</td>
<td>singlet. set</td>
<td>n.a</td>
<td>defined function</td>
<td>analytic function</td>
</tr>
<tr>
<td>[80]</td>
<td>5/3 prop. valve</td>
<td>(s(e, \dot{e}))</td>
<td>1</td>
<td>7</td>
<td>triang</td>
<td>1</td>
<td>7</td>
<td>triang</td>
<td>7</td>
<td>min-max</td>
<td>CoG</td>
</tr>
<tr>
<td>[81]</td>
<td>prop.spool valve</td>
<td>(e / \Delta e)</td>
<td>2</td>
<td>7, 7</td>
<td>triang</td>
<td>3</td>
<td>7, 7, 7</td>
<td>triang</td>
<td>49 (7 \times 7)</td>
<td>3 out</td>
<td>no data</td>
</tr>
<tr>
<td>[83]</td>
<td>proport. valve</td>
<td>(e / \dot{e})</td>
<td>2</td>
<td>7, 7</td>
<td>triang</td>
<td>3</td>
<td>7, 7, 7</td>
<td>triang</td>
<td>147 (3 \times 49)</td>
<td>MAX</td>
<td>CoG</td>
</tr>
<tr>
<td>[84]</td>
<td>proport. valve</td>
<td>(e / \Delta e)</td>
<td>2</td>
<td>7, 7</td>
<td>triang</td>
<td>3</td>
<td>7, 7, 7</td>
<td>triang</td>
<td>49 (7 \times 7)</td>
<td>3 out</td>
<td>max-min</td>
</tr>
<tr>
<td>[85]</td>
<td>3/3 prop. valve</td>
<td>(e / \Delta e)</td>
<td>2</td>
<td>7, 7</td>
<td>triang</td>
<td>3</td>
<td>7, 7, 7</td>
<td>triang</td>
<td>49 (7 \times 7)</td>
<td>3 out</td>
<td>min-max</td>
</tr>
</tbody>
</table>

Table 6. Specification of fuzzy logic units in pneumatic positioning systems.
Table 7. Specification of fuzzy logic units in pneumatic diagnosis and fault detection systems.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Pneumatic System</th>
<th>Analysed Params</th>
<th>No. of Inputs</th>
<th>Input fuzz.sets</th>
<th>Input Function</th>
<th>No. of Outputs</th>
<th>Output fuzz.sets</th>
<th>Output Function</th>
<th>No. of Rules</th>
<th>Fuzzy Operators</th>
<th>Defuz. Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>[88]</td>
<td>Actuator fault</td>
<td>$\frac{x_s}{Q_{out}}$</td>
<td>2</td>
<td>4, 4</td>
<td>triangular</td>
<td>2</td>
<td>4, 4</td>
<td>triangular</td>
<td>32</td>
<td>(2 × 16)</td>
<td>min-max</td>
</tr>
<tr>
<td>[89]</td>
<td>Struts state</td>
<td>5 var. params</td>
<td>5</td>
<td>32 each</td>
<td>Gaussian</td>
<td>2</td>
<td>32,32</td>
<td>Gaussian</td>
<td>49 each in.</td>
<td>min-max</td>
<td>CoA</td>
</tr>
<tr>
<td>[90]</td>
<td>Function. state</td>
<td>$\frac{N}{h}, \frac{mN}{h}, \frac{T}{h}, \frac{mT}{h}$</td>
<td>4</td>
<td>3, 3, 3, 3</td>
<td>triangular</td>
<td>1</td>
<td>5</td>
<td>triangular</td>
<td>81</td>
<td>$3^1$</td>
<td>no data</td>
</tr>
</tbody>
</table>

The issues associated with fuzzy and fault detection for pneumatic systems are similar to those already defined for hydraulic systems. Additionally, there are potential problems related to compressibility and phase transformations that should be considered.

2.2.4. Neuro-Fuzzy Pneumatic Systems

The combination of Fuzzy Logic and Artificial Neural Networks is a technique that has begun to develop in recent years. However, the first publications on its practical implementations can already be found. Živčák et al., in [91], presented a mechanical ventilator developed within research motivated by the COVID-19 pandemic situation. The ventilator pressure was controlled by means of an adaptive neuro-fuzzy inference system. Furthermore, Chen et al. [92] designed a deep fuzzy-neural network controller for a pneumatic flexible joint, and Mawlani et al. [93] proposed an observer-based self-organizing adaptive fuzzy-neural network control for a non-linear, non-affine pneumatic system with unknown dead zone.

The technique of combining fuzzy logic and ANNs is relatively new and is currently in the development phase. However, the already achieved results indicate that it may become a significant method of automatic adjustment of fuzzy logic unit parameters.

3. Discussion

Summarizing the design parameters of the analysed hydraulic and pneumatic fuzzy logic systems, the following observations are worth noting:

- Input signals: two inputs are used in 65% of cases, while one input is applied in 17% of cases. The second group mainly includes sliding mode controllers. Moreover, 32% units (which is about half of two-signal ones) divide the signals into (7, 7) fuzzy sets. Control error $e$ and its change $\Delta e$ or derivative $de/dt$ account for 57% of cases.

- Output signals: the most popular are single-output (57%) and three-output (25%) units. The second group mainly includes fuzzy-PID systems. Output signals are often divided into seven (30%) or five (24%) fuzzy sets.

- Membership functions: input signals are usually divided into triangular (65%) and Gaussian (27%) fuzzy sets. Regarding the output signals, triangular functions account for 59% and 17%, respectively.

- Rule database: the size of the rule base is an especially variable parameter. The number of rules ranges from 3 to over 200. The most common number of rules is 49 (18% cases), which is related to the popularity of two-input, single-output systems that divide each input signal into seven fuzzy sets.

- Inference system: the Mamdani method is used in approx. 82% cases. The rest are Takagi–Sugeno-type methods (14%) and a few proposals for alternative solutions.

- Fuzzy operators: authors declare the use of the most straightforward MIN-MAX operators (29% of studies). However, these are parameters that usually are not specified (65%).

- Defuzzification method: this is specified in approximately two-thirds of the studies. Various algorithms may be used, including Center of Gravity (CoG), Center of Area (CoA), Centroid, Weighted Average, etc.
4. Conclusions

The review presented analyses of the recent publications on fuzzy logic applications within hydraulic and pneumatic systems. Interest in this subject area among scientific centres has remained at a high level for several years, as evidenced by the significant number of publications in leading scientific journals. The authors indicate that the use of fuzzy logic allows the accuracy to be increased and control time to be shortened. This is particularly noticeable in the case of highly non-linear objects, including hydraulic and pneumatic systems. The application of fuzzy logic controllers increases the operational capabilities of devices and reduces energy consumption. Based on the analysed publications, the following detailed conclusions can be formulated:

- Fuzzy logic in hydraulic and pneumatic systems is primarily used for control. The most commonly studied practical application is a fuzzy-PID control system, which includes a traditional PID controller whose parameters are adjusted in real-time by a parallel-connected fuzzy logic unit. A considerably less frequently used solution is a stand-alone fuzzy logic system generating a signal directly for a hydraulic or pneumatic control element.
- The most frequently used environment in research on fuzzy logic is Matlab with Simulink and specialized add-ons such as Fuzzy Logic Toolbox or SimMechanics (approx. 80% of studies). Some research was also conducted in AMESim, MSC ADAMS and LabView systems.
- Fuzzy logic models and controllers are built in the form of standard four-module systems, including fuzzification, inference, rule database and defuzzification.
- Risk assessment and fault detection of hydraulic and pneumatic systems are subject areas in which fuzzy logic algorithms are relatively rarely used. However, there is great potential for development here, resulting from the possibility of uniform recording of various types of parameters in the form of fuzzy sets, as well as simple and logical formulation of rules constituting the basis of the decision-making process.

The following future-oriented conclusions may also be formulated:

- A Takagi–Sugeno inference method is utilised in less than 15% of publications. This method could be used more often, since it has significantly larger possibilities to model non-linearities, which compensation is crucial in hydraulic and pneumatic systems.
- A relatively new feature in the form of a type-2 membership function is used only in two publications. This function type could be used more often.
- The advantageous solution for future research can be the construction and training of neuro-fuzzy systems. Combining the advantages of neural networks and fuzzy logic could provide greater possibilities for tuning fuzzy logic unit parameters in the ANN-like training process.
- Automatic or autonomic parameter adjustment methods of the fuzzy logic units are not often used. Up to now, expert knowledge-based or trial-and-error methods have usually been utilised. However, there are some promising solutions based on GA or PSO that could be further developed.

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**Conflicts of Interest:** The author declares no conflict of interest.

**Nomenclature**

**Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAv</td>
<td>Centre Average defuzzification method</td>
</tr>
<tr>
<td>CoA</td>
<td>Centre of Area defuzzification method</td>
</tr>
<tr>
<td>CoG</td>
<td>Centre of Gravity defuzzification method</td>
</tr>
<tr>
<td>FMEA</td>
<td>Failure Mode &amp; Effects Analysis</td>
</tr>
</tbody>
</table>
GA Genetic Algorithm
LFC Load Frequency Control technique
PD Proportional–Derivative
PID Proportional–Integral–Derivative
PSO Particle Swarm Optimization method
PWM Pulse-Width-Modulation control technique
SoC State-of-Charge (battery)
SoM, MoM, LoM Smallest-, Medium-, Largest- of Maxima defuzzification method
T−S Takagi–Sugeno inference method
WAvg Weighted Average defuzzification method

Parameters
acc acceleration
de/dt, de/dt, ˙e control error derivative
ei, ei control error
Δe, Δei control error change
min, MIN, prod fuzzy product operator
max, MAX fuzzy sum operator
pi, ṗi pressure
Q, Q̇out flow rate
s(args) sliding-mode function
Ti, Ṫi torque
vc velocity
x, xi, x1, x2 position

References


41. Ghini, Y.; Vaccara, A. A method to perform prognostics in electro-hydraulic machines: The case of an independent metering controlled hydraulic crane. *Int. J. Hydromechatron. 2018*, *1*, 197–221. [CrossRef]


50. Elsayed, M.E.; Attia, A.A.; Abdelrahman, M.; Attia, E.A. Dimensioning of the hydraulic gravity energy storage system using Fuzzy logic based simulation. *J. Energy Storage* 2021, 42, 103151. [CrossRef]
63. Woś, P.; Dindorf, R.; Takosoglu, J. Fuzzy Controller to Control the Active Air Suspension. *Arch. Automot. Eng.* 2020, 89, 75–86. [CrossRef]
64. Ho, C.M.; Ahn, K.K. Adaptive Fuzzy Output Feedback Control Design for Pneumatic Active Suspension with Unknown Dead Zone. *IEEE ACCESS* 2023, 11, 66858–66871. [CrossRef]
65. Ho, C.M.; Ahn, K.K. Design of an Adaptive Fuzzy Observer-Based Fault Tolerant Controller for Pneumatic Active Suspension With Displacement Constraint. *IEEE ACCESS* 2021, 9, 136346–136359. [CrossRef]


79. Šitum, Z.; Corić, D. Position Control of a Pneumatic Drive Using a Fuzzy Controller with an Analytic Activation Function. Sensors 2022, 22, 1004. [CrossRef] [PubMed]


83. Takosoglu, J.; Janus-Galkiewicz, U.; Galkiewicz, J. A Design of a 2-DoF Planar Parallel Manipulator with an Electro-Pneumatic Servo-Drive. Energies 2022, 15, 8482. [CrossRef]

84. Takosoglu, J.; Janus-Galkiewicz, U.; Galkiewicz, J. A Design of a 2 DoF Planar Parallel Manipulator with an Electro-Pneumatic Servo-Drive—Part 2. Energies 2023, 16, 2970. [CrossRef]


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