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Fuzzy Assessment Algorithm for Ladder Programming

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Abstract. This paper* proposes an assessment algorithm to measure the quality in ladder programming for programmable logic controllers (PLCs). The proposed quality metrics involve the criteria of simplicity, reconfigurability, reliability, and flexibility. The value of each metric criterion is normalized between 0 and 1. A fuzzy assessment algorithm is developed to select the best controller design among a set of developed ladder programs for the same application. A single tone membership function is used to represent the metric criterion for each controller between 0 and 1. The fitness of each controller is evaluated as the minimum value of all the applied metric criteria. Thereafter, the decision making to select the best logic design is obtained as the maximum value of all fitness values. The developed fuzzy assessment algorithm is applied to real time discrete event systems. These systems are a pneumatic cylinder and a conveyor belt where each of them performs a repeated sequence. The obtained results affirmed the potential of the proposed algorithm to assess the quality of the designed ladder programs. The main contribution of this paper is to define a methodology to measure the quality for programs written in ladder diagrams.

Introduction

The Programmable Logic Controller (PLC) is used widely in industries to control processes and manufacturing systems. There are several analytical approaches for developing PLC programs (Donald *et al*., 2007). During this decade, few researchers addressed the problem to investigate the quality of logical controller programs. Lee and Hsu developed a unified comparison approach to adequately evaluate the ladder diagram (LD) and Petri nets (PN) by using the IF-THEN transformation (Lee and Hsu, 2001). The metric results showed that the (PN) is simpler and more flexible than the (LD). This result is fairly biased because (PN) is not a direct programming language for PLCs; it can be used for logic validation. PNs are compact as a graphical tool for modeling and simulation. Frey used a transparency metric to evaluate different aspects in the logic control algorithm using (PN) (Frey, 2002).

His technique helps to check if this algorithm is easy to understand or not. Other researchers are interested in measuring the difficulties to develop the sequence control; they developed a metric criterion to estimate the required time for development in designing Ladder, Petri nets, and modular finite state machines (Lucas and Tilbury, 2003) and (Lucas and Tilbury, 2005).

Some researchers are interested in a software reverse engineering process as Younis and Frey; they presented a survey on the different methods to formalize the existing PLC programs (Younis and Frey, 2003). The process of formalization for already implemented PLC code is a reinterpretation or translation of the PLC program from one form to another. In general, the research work on software assessment for PLCs can be categorized into the following directions:

- Logic validation prior to develop the PLC code
- Development process itself (i.e. writing the code)
- Quality measurements of the PLC code product
- Formalization techniques to translate the PLC code to another form (verification)

This paper focuses on the quality measure of the control program after it has been carried out as a control product. Qualitative analysis and performance measure of ladder programming are seldom discussed. This point is very important to check the software quality as the end product. However, partners' relationship in PLC applications involves: customer (end user), consultant, and the system integrator. The relationship and the role of each partner are given in Table 1.

Table 1. Partners' Relationship

Partner	Relationship and important roles
Customer	• Define the required service and user requirements • Deliver all required information to the consultant Sign a detailed agreement with the consultant
Consultant	• Investigate the problem and apply the system analysis to define a complete hardware and software solution. • Propose the detailed agreement to the customer with a corresponding quotation • Sign an agreement with a system integrator • Supervise the different tasks carried out by the system integrator and guarantee the quality to the customer Prepare a detailed documentation of the implemented tasks to the customer
System integrator	• Sign an agreement with the consultant • Deliver the system components (hardware and software) • Perform different technical tasks (integration and installations) • Conduct all the detailed documentations to the consultant

In this paper, metric criteria for simplicity, reconfigurability, reliability, and flexibility are considered. However, there are also other interesting aspects such as: functionality, safety, maintainability (portability), usability, and efficiency (Frey, 2002). These points are out of scope of this paper.

The paper is organized as follows: first section gives the motivations to measure the software quality for PLCs applications. Second section presents the proposed metric quality criteria for ladder programming design. Third one involves the developed fuzzy assessment algorithm to take the decision which controller is the best. Fourth one investigates the validity of the developed algorithm via a real time application to control a repeated sequence of a pneumatic cylinder and a conveyor belt system. Last section ends the paper with highlighting the conclusion and suggestions for the future work.

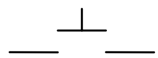
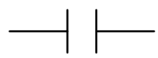
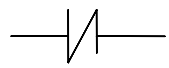
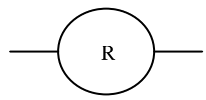
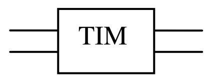
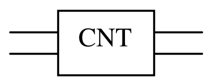
Quality Criteria

In 1993, the international electro-technical commission published the IEC 1131 international standards for programmable controllers (IEC, 1993), (Lee and Hsu, 2005) and (Feldmann *et al*., 1999). Part 3 of this standard defines a suite of five programming languages:

- Ladder diagram, has its roots in the USA. It is based on the graphical presentation of relay ladder logic.
- Instruction list has its European counterpart. As textual language, it resembles assembler.
- Functional block expresses the behavior of a controller as a set of interconnected graphical blocks, like in electronic circuit diagrams.
- Structured text is a very powerful high-level language that is close to Pascal language.
- Sequential flow chart, its elements are defined for structuring the internal organization of programmable controller programs and function blocks.

Ladder diagram is most commonly used in PLC applications because it replaces directly the existing hardwired-relay components in the power and control cabinets. Basic elements are shown in Table 2. These symbols involve: push buttons, limit switches, relay coils, timers, counters, and solenoids.

Table 2. Ladder diagram elements

Element	Graphical symbol
Push button	
Normally open contact	
Normally closed contact	
Relay coil	
Timer	
Counter	
Solenoid	

For application software; the ISO/IEC 9126 standard defines software quality characteristics as: "*A set of attributes of software product by which its quality is described and evaluated*" (Frey, 2002). The following subsections present the proposed criteria to measure the quality of a ladder diagram.

A. Simplicity

The controller represents in its heart a set of IF-THEN production rules. The rule simplicity can be considered as a measuring criterion to investigate the software quality. The simplicity of rule i is defined as:

$$S_i = \frac{E_i}{E_i + F_i} \tag{1}$$

where E_i Number of input elements in the rule i (contacts)
F_i Number of operators in the rule i (and/or logic functions with two inputs)

The above simplicity metric criterion decreases its value as the rule becomes more complicated. The simplicity criterion has a maximum value as one when a single contact only activates the rule output. The global simplicity criterion P_1 for a complete ladder diagram is defined as the average of the obtained results using equation (1) for all the rules in the program.

$$P_1 = (1/n)\sum_{i=1}^{n} S_i \tag{2}$$

where n Total number of controller rules (networks) in the ladder program

B. Reconfigurability

The ability to change or to replace software modules is related to how much the number of operations is reduced. This concept makes it easy to understand the functionality of the logical controller and facilitate its debugging. Hence; the reconfigurability criterion P_2 is defined as

$$P_2 = \frac{E}{E + F} \tag{3}$$

where: E Total number of input elements
F Total number of operators

The maximum value of P_2 is equal to one when the rules are independent and F has a zero value.

C. Reliability

Reliability is the correctness and robustness of the control algorithm proved by verification and validation under minimal assumptions about the controller's environment (i.e. inclusion of possible errors) (Frey, 2002). Some PLCs have the capability to run a fault subroutine when abnormal condition will stop the program. To be able to perform this task, auxiliary markers as flags and watchdog timers are used. Therefore, the use of these elements for fault routine will increase the system reliability and also its safety to operate. The reliability criterion is defined as:

$$P_3 = \frac{A}{E} \tag{4}$$

where A Total auxiliary markers in ladder diagram

D. Flexibility

The controller is less flexible when the complexity in sequence increases. That means, more flexible controller has the ability to change the sequence more easily. Lee and Hsu affirmed that the degree of programming flexibility can be analyzed by observing the increasing ratio of either the number of elements with respect to the operators or the number of present rules with respect to the operators (Lee and Hsu, 2001). Consequently, flexibility will be decreased as the complexity of a sequence increases. However, this definition has a problem when the number of operators F has a zero value and it can't be used easily to compare between different designs. Therefore, another definition is proposed as the ratio between the number of rules n and the total number of input elements E in the ladder diagram:

$$P_4 = \frac{n}{E} \tag{5}$$

The above criterion is an absolute metric criterion and depends on the controller design itself.

Fuzzy Assessment Algorithm

Fuzzy logic is developed by Lotfi Zadeh to deal with uncertainty in system representation (Zadeh, 1965). During the past decade, fuzzy logic has found a variety of applications in various fields ranging from sensors, motors, steam turbines, robotics, and intelligent controllers to medical diagnosis and decision making (King and Mamdani, 1977), (Lee, 1990), and (Chin-Teng and George, 1991). The integration of this logic into process engineering and information systems improved the machine intelligence (Zadeh, 1992). In our development, there is a resemblance between the proposed quality criterion and the membership function where both of them lie between zero and one. Hence, single tone membership functions are used to express the quality of each design as shown in Fig. 1.

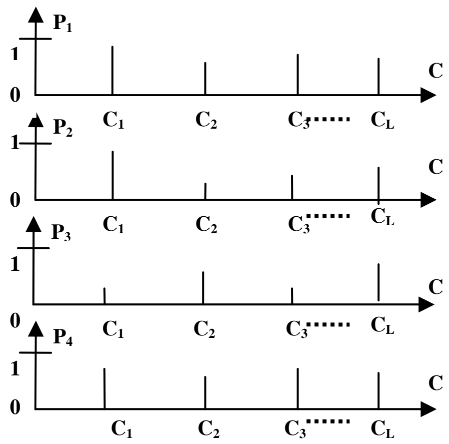


Fig. 1. Membership functions.

The universe of discourse is discrete (C_1: 1st ladder diagram, C_2: 2nd ladder diagram, …,and C_L: Lth ladder diagram) for the same application. Each quality criterion is normalized and has a value between zero and one, its value corresponds directly to the degree of membership. The fitness F_j of controller j is evaluated as the minimum value of all computed criteria corresponding to this controller as follows:

$$F_j = \text{Min}(P_{1j}, P_{2j}, P_{3j}, P_{4j}) \quad ; j = 1,2,...,L \qquad (6)$$

P_{1j}, P_{2j}, P_{3j}, and P_{4j} are the metric values of the performance criteria for controller j.

Finally, the best controller is carried out using the maximum fitness value as follows:

$$\text{Best controller} = \text{Max}\left(F_1, F_2, ..., F_L\right) \qquad (7)$$

Equations 6 and 7 are the core of the fuzzy decision making whereas the min-max inference is applied.

The proposed fuzzy assessment algorithm is summarized as follows:

BEGIN
DO (for each controller)
Compute Pi {equations (2,3,4, and 5)}
Compute the fitness value using equation (6)
END DO
Best controller = decision using equation (7)
END

In the next section, the above algorithm is applied to real time discrete event systems. These applications will investigate the potential of the proposed algorithm.

Applications

Application 1: Pneumatic cylinder

The system consists of a pneumatic cylinder as shown in Fig. 2 to perform a forward stroke and then retracts (Lee and Hsu, 2004). In this figure, the specification A+ indicates a forward stroke and A- indicates return stroke sequentially. While, **a0** and **a1** are normally open limit switches to end each stroke.

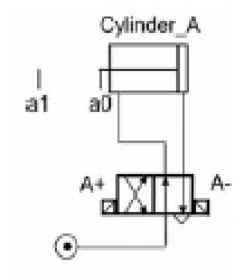


Fig. 2. Pneumatic cylinder. (Lee and Hsu, 2004).

For example, when the end of cylinder A contacts the limit switch a0, then a0 is closed, meaning that cylinder A is at the end of its return stroke. The whole system includes 3 input sensors corresponding to two limit switches and one push button **Pb** for starting the system, and 2 output actuators corresponding to two solenoid valves A+ and A-. Three different ladder diagrams are carried out to perform the repeated sequence {A+, A-} as shown in Figs. 3, 4 and 5.

The controllers (Figs. 3, 4 and 5) are evaluated using the developed fuzzy assessment algorithm and the obtained results are given in the Table 3.

Table 3. Performance metrics (pneumatic cylinder)

Ladder Design / Parameters	Ladder diagram C1	Ladder diagram C2	Ladder diagram C3
Elements E	10	14	20
Operators F	6	6	12
Rules n	2	4	4
P1	0.57	0.785	0.57
P2	0.5	0.75	0.25
P3	0.67	0.6	0.67
P4	0.8	0.71	0.8
Controller fitness	0.5	**0.6**	0.25

In applying the fuzzy assessment algorithm, the best design is C2 for the criterion P1 and P2 while C1 and C3 are the best designs for P3 and P4. The best overall performance is obtained for the second controller which attains the maximum fitness at the value (0.6).

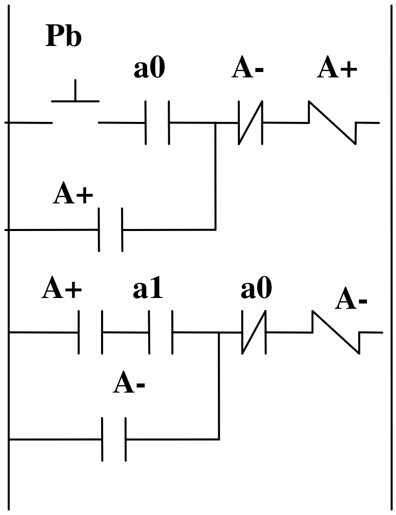


Fig. 3. Ladder diagram (C1).

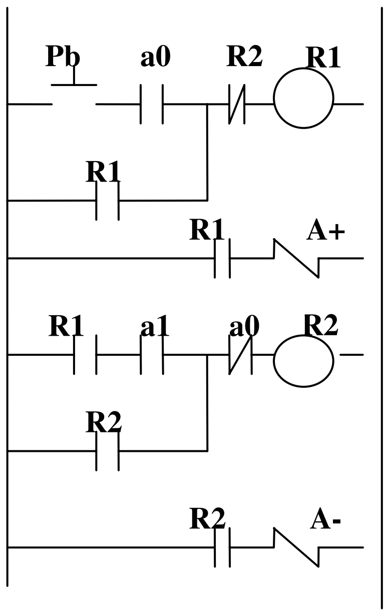


Fig. 4. Ladder diagram (C2).

Comparison with Lee and Hsu algorithm

The algorithm proposed by Lee and Hsu is very simple to compare between ladder diagram and Petri net controller for the same application (Lee and Hsu, 2004). Their algorithm depends on two measures:

- Number of rules
- Number of logical operators.

They applied the sum of the two measures to evaluate the controller structure. The best controller is the one that has a less value of this criterion. In applying this criterion to the results in table 3; the first structure is the best. The result is different than the results obtained using proposed fuzzy algorithm because the

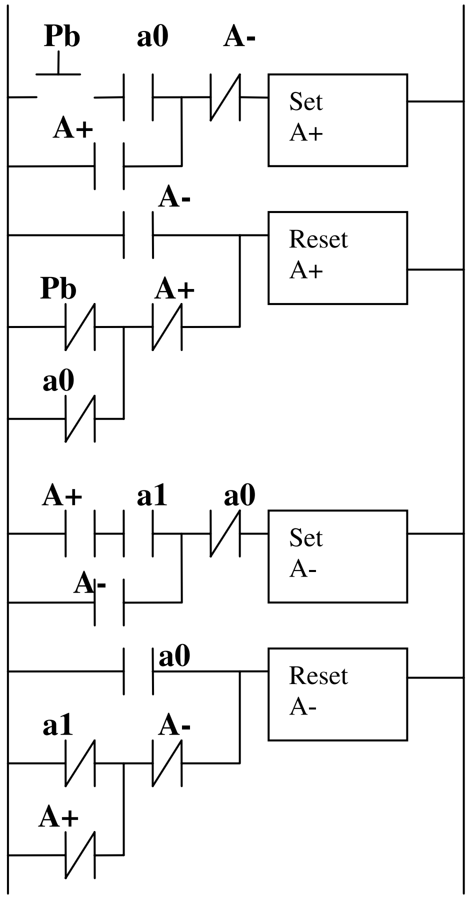


Fig. 5. Ladder diagram (C3).

summation of the number of rules and number of operators measures only the simplicity of the structure. The proposed fuzzy algorithm compromises between multi objective criteria and it is more practical in real time applications.

Application 2: Conveyor belt system

The proposed fuzzy assessment algorithm is applied to a single track conveyor belt. The conveyor belt consists of a single-track belt that is equipped with an optical sensor for detecting work pieces at the end of conveyor track and an inductive sensor in the middle of track as shown in Fig. 6.

The actuator is a DC motor (24V) with adjustable speed and relay circuit for clockwise and Anti-clockwise rotation interfaces. The whole system includes three inputs corresponding to an optical sensor, an inductive sensor and one pushbutton for starting the system.

The system has two output actuators corresponding to motor clockwise and anti-clockwise rotation directions. The I/O assignment to the PLC is given in Table 4.

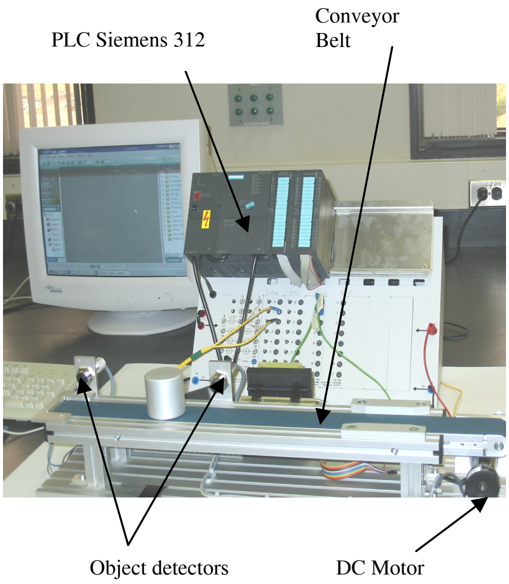


Fig.6. Conveyor belt system.

Table 4. I/O Assignments to PLC

PLC I/O	Address	Function
Input	I124.2	Start pushbutton
Input	I124.1	Optical sensor B10
Input	I124.0	Inductive sensor B11
Output	Q124.0	Motor anti-clockwise
Output	Q124.1	Motor clockwise

The ladder diagram in Fig. 7 is developed on a PC using the integrated development environment software SEMATIC (step 7 lite) of Siemens; then the program is downloaded into the PLC flash memory via a serial interface RS232.

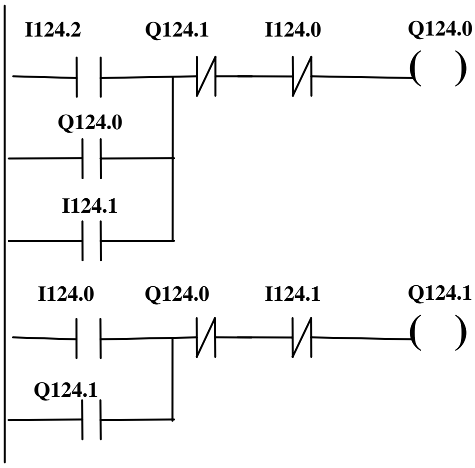


Fig.7. Ladder diagram (Design 1).

This program achieves the following repeated sequence:

- When the start pushbutton is pressed (I124.2); the conveyor start to move in forward direction (Q124.0 is ON and Q124.1 is OFF)
- When the sensor B11 detects the cylindrical object on the conveyor, then the conveyor moves in the reverse direction (Q124.0 is OFF and Q124.1 is ON)
- When the sensor B10 detects the cylindrical object on the conveyor, then the conveyor moves again in the forward direction (Q124.0 is ON and Q124.1 is OFF)

As the sequence is repeated; the cylindrical object is moving repeatedly between the two sensors.

The following design performs the same sequence using the auxiliary markers R1 and R2 to activate Q124.0 and Q124.1 respectively.

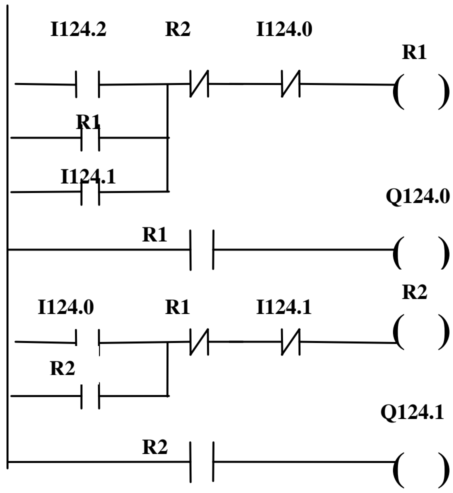


Fig.8. Ladder diagram (Design 2).

Table 4. Design parameters (conveyor system)

Ladder Design / Parameters	Ladder diagram C1	Ladder diagram C2	Ladder diagram C3
Elements **E**	9	11	9
Operators **F**	7	7	5
Markers **A**	4	6	4
Rules **n**	2	4	4
P1	0.56	0.78	0.65
P2	0.56	0.61	0.64
P3	0.44	0.55	0.44
P4	0.22	0.36	0.44
Controller fitness	0.22	0.36	**0.44**

The three controllers are evaluated using the developed fuzzy assessment algorithm. Table 4 and Fig. 10 show the design parameters.

The following design performs the same sequence using set and reset flip/flop actions.

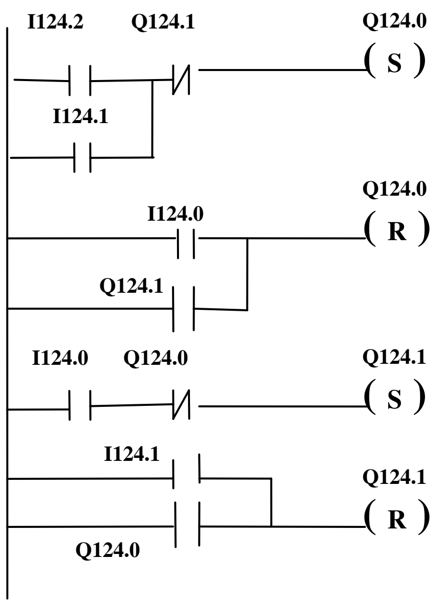


Fig.9. Ladder diagram (Design 3).

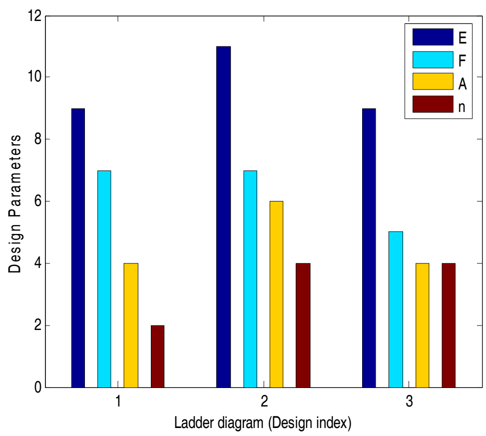


Fig. 10. Ladder diagram parameters.

The above figure shows the important parameters for each design (E: number of input elements, F: number of operations, A: number of auxiliary markers, and n: number of rules per each design). Table 4 shows also the obtained results in applying the fuzzy assessment algorithm. The best overall performance is obtained for the third controller which attains the maximum fitness value (0.44). It is clear that the worst design is C_1. It does not attain the maximum value for any of the above criteria. This result is due to its complexity whereas it has a less number of rules. The design C_2 is the best one for the criteria P_1 and P_3 that means this design is more simple and reliable with extra number of auxiliary markers. The design C_3 is the best one for the criteria P_2 and P_4 that means this design is more reconfigurable and flexible with less number of operators. The number of operators is reduced due to the automatic latching using set and reset actions. This design is the best one. It has the maximum fitness in applying the proposed fuzzy assessment algorithm.

Conclusion

Metric performance criteria are developed for ladder programming. The metric criteria include: simplicity, reconfigurability, reliability, and flexibility. A simple min-max fuzzy inference is developed to assess the ladder program quality. The proposed algorithm is applied to both a pneumatic cylinder and a conveyor belt where each system performs a repeated sequence. The obtained results affirmed its potential to assess the quality of the designed ladder diagram and to take the decision which design is the best one. However, the proposed fuzzy assessment algorithm can be also applied to any other representation of logical controllers where the core part is a set of IF-THEN rules that control the industrial system. The logical controller can be transformed to a unified domain that is so-called, IF-THEN representation. Thereafter, the algorithm can be applied to each one of them. Consequently, the fitness of each controller could be evaluated using the developed fuzzy algorithm. That means the proposed algorithm is not restricted only to ladder diagram. In the future, other performance criteria can be also investigated such as: usability, portability, and maintainability. The assessment between different representations could also be considered.

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خوارزم المنطق المتباين لتقييم البرمجة بلغة الدرج

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(قدم في ٢٠٠٨/٤/١٣م؛ وقبل للنشر في ٢٠٠٨/١١/٠٤م)

الكلمات المفتاحية: تقييم البرمجيات، المحكم المنطقى المبرمج، برمجة الدرج، المنطق المتباين، تصميم منطقى.

ملخص البحث. المحكمات المنطقية تستخدم كثيرا فى الصناعة وخاصة فى خطوط التجميع والإنتاج. ومن أكثر النماذج شيوعا فى الاستخدام المحكم المنطقى المبرمج. وبناءا على خبرة المبرمجين يتم الحصول على تصميمات مختلفة لنفس التطبيق من حيث الهيكل أو مكونات البرنامج. يهدف هذا البحث الى قياس جودة برمجيات التحكم (البرمجة ذات الدرج Ladder Programming) وذلك بعد تصميمه وقبل استخدامه فى التطبيق الصناعى. قياسات الجودة المقترحة تشمل أربع معايير: السهولة، إعادة الهيكلة، الاعتمادية، والمرونة. جودة تصميم المحكم لكل معيار يمكن تمثيلها باستخدام single-tone membership function. وباستخدام عملية الاستدلال للمنطق المتباين Min-Max Fuzzy Inference يمكن الحصول على معيار كمى يعبر عن جودة تصميم كل محكم. تم اختبار الخوارزم المقترح للتحكم فى حركة ترددية لأسطوانة تعمل بضغط الهواء وأثبتت النتائج فاعليته وقابليته للاستخدام. وكذلك تم تطبيق الخوارزم المقترح لقياس الجودة على سير يتم التحكم فيه عمليا باستخدام PLC Siemens S7 وأثبتت النتائج فاعليته فى قياس الجودة لبرمجيات التحكم التى تم تصميمها لنفس الغرض.