

MULTI AXIS FUZZY CONTROL AND PERFORMANCE ANALYSIS FOR AN INDUSTRIAL ROBOT

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Abstract -Robot control systems can be considered complex systems, the design of a controller involving the determination of the dynamic model for the system. Fuzzy logic provides functional capability without the use of a system model or the characteristics associated with capturing the approximate, varying values found in real world systems.

Development of a multi-axis fuzzy logic control system was implemented on an industrial robot, replacing the existing control and hardware systems with a new developmental system. During robot control no adaptation of the rule base or membership functions was carried out on line; only system gain was modified in relation to link speed and joint error within predetermined design parameters. The fuzzy control system had to manage the effects of frictional and gravitational forces whilst compensating for the varying inertia components when each linkage is moving. Testing based on ISO 9283 for path accuracy and repeatability verified that real time control of three axes was achievable with values of 938 μ m and 864 μ m recorded for accuracy and repeatability respectively.

I. INTRODUCTION

Fuzzy set theory and fuzzy logic theory was introduced which allowed vague inexact and poorly defined concepts to be defined by a mathematical process. Our life and world obey the *principle of compatibility*; where, in theory the closer a person looks at a 'real world' problem, the solution to that problem becomes progressively fuzzier [1]. Stated in simpler terms; as systems become more complex the human ability to make well defined and significant statements about a system's behaviour diminish; a point is eventually reached where precision and significance (relevance) become almost exclusive characteristics [2].

In industrial applications where precise system models cannot be obtained or where systems are too complex, fuzzy logic control can provide a solution. Based on the experience of human operators, who derive the fuzzy rule base for the system, these fuzzy control systems often give better results than the original conventional PID type control systems [3].

Fuzzy control can provide a performance advantage and may be applied to the majority of control problems whilst not always providing the simplest solution. The use of fuzzy

logic in control has mainly been due to the ease of implementation, based on existing expert knowledge and the adaptability to incorporate such technology for use in non-linear systems.

II. MULTI AXIS CONTROL

Research work on the development of the single axis fuzzy based control software has led to the development of multi-axis control for an industrial robot using a continuous path algorithm. The move from single axis to multiple axis control has demanded the development of a much more complex and innovative software-based controller for use with an industrial robot.

The main additions to the existing single axis control system included:

- Robot position calibration to enable accurate co-ordinate transformations
- An efficient inverse kinematics algorithm
- Linkage speed and error monitoring
- Graphical rule firing monitoring

In order to achieve multi-axis control, initially, derivation of the inverse kinematics equations for the robot required computation. The main problems arose in trying to determine single valued functions for the range of possible angles when calculating the transformation from the Cartesian space to the joint angle space. The inverse kinematics code was incorporated as part of the main multi-axis fuzzy control program, although testing was initially carried out on individual axes to verify the function of each section of the program. Additional software was also developed to check for multiple solutions and viable inverse solutions to ensure that the required co-ordinates lay within the robot workspace.

By monitoring joint position via the DC servo motor optical encoders the robot could be 'tracked' continuously at predetermined points along a generated path and in real time. A continuous path algorithm also determined the path of the TCP (Tool Centre Point).

With the development of three individual fuzzy axis control programs, the aim was to modify and combine the existing

control programs in order to develop a control program to provide multi-axis control.

Figure 1.0 shows the three axes, Theta, X and Z on the Industrial robot that were developed for multi-axis control.

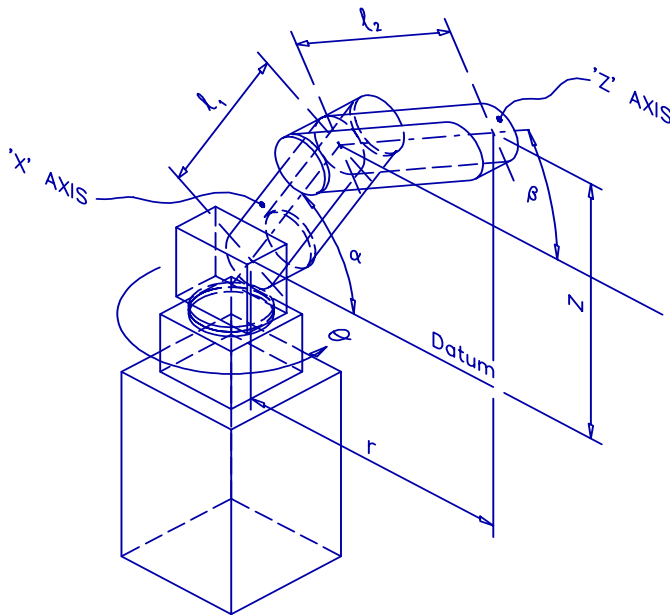


Figure 1.0: Three degrees-of-freedom planar arm

III. MEMBERSHIP FUNCTIONS AND RULE BASE

Further examination of the membership functions for Change in Error, Error and Output was investigated for further tuning of the multi-axis controller. The major change to the fuzzy controller for the multi-axis system was the reduction of the rule base, the number of rules being reduced from 49 for the single axis controllers to 15 for multi-axis control. Although individual axes gave acceptable performance the large rule base used by individual axis programs could not be transposed to three-axis real time control due to time slicing placing a high overhead on processing time and hence making the system both unreliable and unstable.

The multi-axis controller uses three independent rule bases for the Theta, X and Z axes within a single C++ header file; a typical single axis rule base is shown in Table I.

| | | <i>E</i> | | | | |
|------------|----|----------|----|----|----|----|
| | | LN | MN | ZE | MP | LP |
| ΔE | CP | MN | SN | ZE | SP | MP |
| | ZE | LN | MN | ZE | ZE | SP |
| | CN | LN | LN | MN | SN | ZE |

TABLE I
TYPICAL THREE-AXIS 15 RULE FUZZY MATRIX

The construction of the fuzzy rule base was based originally on a PD controller. Whilst manual tuning of the rule base for this work confirmed that the rules could not be further modified to provide any overall significant benefit to system performance, it was acknowledged that the introduction of rule base tuning could possibly provide further enhancements and improvements to system performance based on the current control algorithms.

The development and implementation of a simple graphical interface was introduced in the fuzzy controller user interface as an aid for manual rule tuning. The graphical display consisted of five by three matrix with segments representing and displaying the actual rule being 'fired' as a move was being undertaken by the axis. A range of colours was used to show the actual 'weight' of each rule as it fired for both the change in error and error functions.

An external clock pulse provided a reference for determining both arm speed and the maximum design speed that the robot was set to achieve during a specific operation, the design speed variable being set by the user. The speed of a link was determined by sampling the time for one program loop against the measured change in encoder counts. The scaling factors, sometimes referred to as 'fuzzy system gain' were also influenced by the speed variable. Whilst the Error value within the fuzzy control program was scaled by a set integer value, the Change in Error value was scaled by the speed variable.

IV. INTERNATIONAL STANDARD – PATH ACCURACY AND REPEATABILITY

Path accuracy and repeatability are shown in Figure 2.0 as described by BS EN ISO 9283:1998, which describes path accuracy as characterising the ability of a robot to move its mechanical interface along the command path in the same direction n times [4].

The path accuracy is determined by two factors:

1. The difference between the positions of the command path and the barycentre line in the cluster of the positions in the attained paths;
2. The difference between command orientations and the average of the attained orientations (i.e. orientation accuracy).

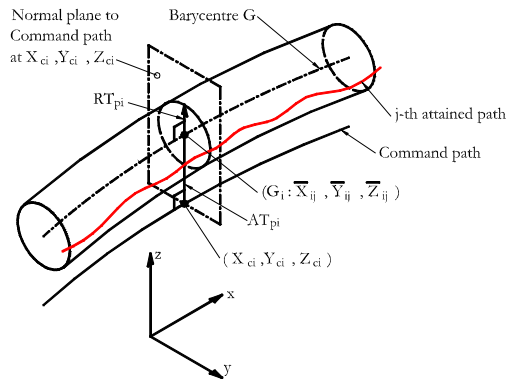


Figure 2.0: Path accuracy and path repeatability for a command path

From Figure 2.0:

AT and RT represent accuracy and repeatability respectively; G represents the barycentre of a cluster of attained poses; i indicates the i-th abscissa; j indicates the j-th cycle; c indicates command; p indicates position; x, y and z indicate the linear coordinates along the x, y and z axes.

The Improvement of Robot Industrial Standardisation (IRIS) project highlighted deficiencies in the international standard, and in addition questioned the experience of companies using and adopting the ISO 9283 standard [5].

Based on Schröder's research and the BS ISO 9283 standard it is clear that there is still no universally adopted standard for robot performance testing. Therefore for this work three-axis testing of the fuzzy control system was based on selected criteria outlined in BS ISO 9283.

As link velocity was not a direct control function of the fuzzy control system, the importance of link trajectory and positional accuracy was selected for further examination. Path accuracy and repeatability were chosen as the most suitable tests for the fuzzy control system with an additional zero load test to analyse the control function accuracy for a five consecutive linear path move.

V. PATH ACCURACY (AT) AND PATH REPEATABILITY (RT) RESULTS

For ten cycles in the same direction with a 5kg load (100% of rated load):

- Horizontal, 200 mm square, 4 paths
- Inclined, 200 mm square, 4 paths
- Horizontal, 200 mm circle, 1 path
- Inclined, 200 mm circle, 1 path

Positional data from the tests was based on the initial retrieval of individual axis encoder positions, this data being

collected and converted to Cartesian coordinates by a separate data logging PC and bespoke conversion program.

Path accuracy and repeatability experimentation was conducted by implementing four individual tests as shown in Figure 3.0, which also shows the test path numbers.

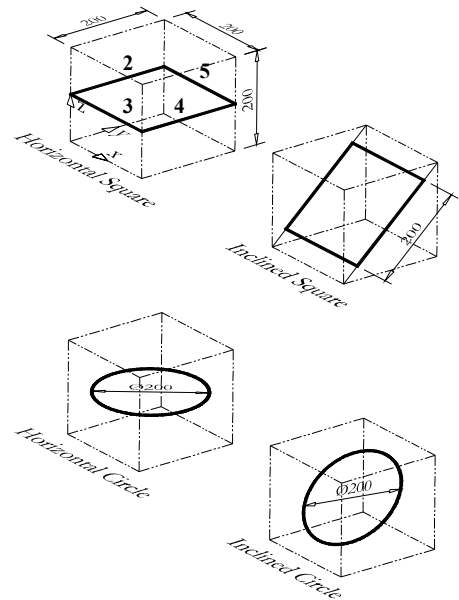


Figure 3.0: Accuracy and repeatability test paths

All tests were conducted using a 5kg load specified as the maximum load by the original robot equipment manufacturers; tests were conducted and results collected for ten cycles for each path. The tests were based on the path accuracy and repeatability test definitions contained within ISO 9283.

The values for path accuracy (AT_p) and path repeatability (RT_p) were calculated and the corresponding results for all four tests are shown in Tables II to V.

| Horizontal 200 mm Square | | |
|--------------------------|----------------------|----------------------|
| Path number | AT _p (μm) | RT _p (μm) |
| 2 | 991 | 955 |
| 3 | 961 | 982 |
| 4 | 1022 | 995 |
| 5 | 979 | 930 |

TABLE II
HORIZONTAL 200MM SQUARE - TEST PATH RESULTS

| Inclined 200 mm Square | | |
|------------------------|-----------------------|-----------------------|
| Path number | ATp (μm) | RTp (μm) |
| 2 | 1091 | 917 |
| 3 | 959 | 999 |
| 4 | 1142 | 1129 |
| 5 | 938 | 864 |

TABLE III
INCLINED 200MM SQUARE - TEST PATH RESULTS

| Horizontal 200 mm Circle | | |
|--------------------------|-----------------------|-----------------------|
| Path number | ATp (μm) | RTp (μm) |
| 1 | 1169 | 886 |

TABLE IV
HORIZONTAL 200MM CIRCLE - TEST PATH RESULTS

| Inclined 200 mm Circle | | |
|------------------------|-----------------------|-----------------------|
| Path number | ATp (μm) | RTp (μm) |
| 1 | 1087 | 960 |

TABLE V
INCLINED 200MM CIRCLE - TEST PATH RESULTS

These tests were performed to give an indication of system performance whilst operating at the specified maximum original equipment load. Performing the various tests was used as a method to assess the functionality and ability of the fuzzy control system in coping with the various test paths. The tests also served as a mechanism in assessing system performance due to the additional demands placed on the controller as a consequence of variations in system overheads. From Tables II and III a data summary is presented for both accuracy and repeatability for the horizontal and inclined 200 mm squares; this data is shown in Figures 4.0 and 5.0 respectively.

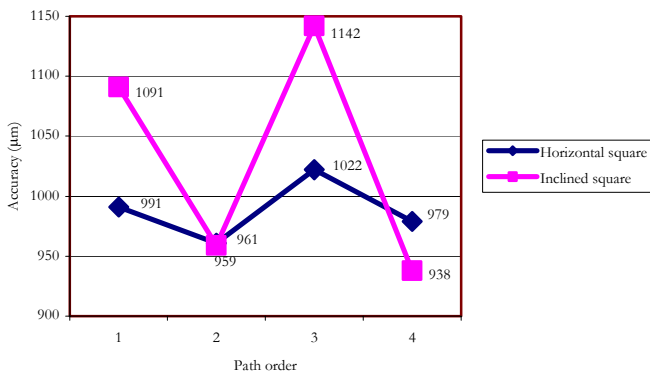


Figure 4.0: Data summary: path accuracy – horizontal and inclined squares

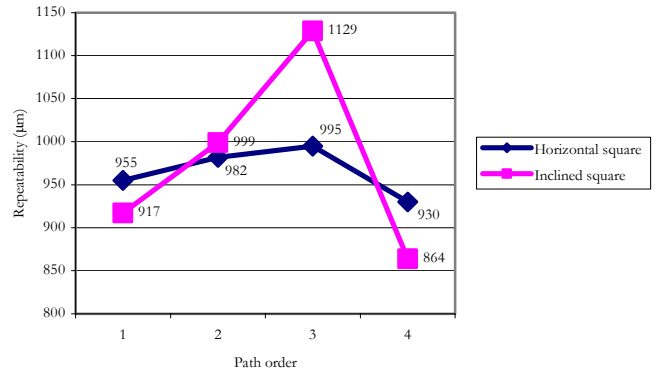


Figure 5.0: Data summary: path repeatability – horizontal and inclined squares

From Figures 4.0 and 5.0 based on accuracy and repeatability data the following two observations may be made:

Repeatability: Path 4 provided the worst results for path repeatability for both the horizontal and inclined square, this path demanding the greatest output motor torque. The values for the horizontal and inclined square were only separated by $134\mu\text{m}$, indicating that the control system could maintain the same level of performance for the more demanding inclined test.

Repeatability was encouragingly lower in all cases when compared with accuracy values, with the exception of Path 3 horizontal square and Path 3 inclined square, however values were only $20\mu\text{m}$ and $40\mu\text{m}$ higher (worse) respectively.

Repeatability values for the inclined circle and horizontal circle were separated by $74\mu\text{m}$ indicating that the control system could adjust, these tests being the most demanding of all the tests in terms of control system loading due to greater system overheads.

Accuracy: Values for accuracy for all tests were reasonably uniform and closely matched. Accuracy values for the inclined circle and horizontal circle were similar with $82\mu\text{m}$ separating the results.

Paths 2, 3 and 5 demanded smaller output motor torque when compared to Path 4. This was supported by the data collected for path accuracy and repeatability for both the horizontal and inclined square, these paths demonstrating comparatively lower accuracy and repeatability values.

Path 4 was expected to produce the worst results in terms of accuracy and repeatability due to the comparative extended reach of the links required for this move. As a consequence of the move the demands placed on amplifiers to drive individual axis motors was increased, these demands being particularly critical for the X axis motor. The increased

demands made by the X axis motor resulted in an overall reduction in system performance. This supposition was supported by individual axis encoder error measurements calculated as a result of further experimentation undertaken on Path 4.

VI. INDIVIDUAL AXIS ERROR

Although repeatability and accuracy values were determined for three-axis control, an additional test was implemented to determine which particular axis, if any, was the most inaccurate. Previous work for single-axis control had already highlighted that the X axis had been the most challenging of the three axes to control. Additional tests were carried out to confirm this supposition.

From Figures 4.0 and 5.0 it is clear that for both accuracy and repeatability Path 4 presented the worst results. Therefore, Path 4 on the horizontal square was selected to determine individual axis error values.

Each path was divided into 1,000 segments also creating a set of 1,000 'nodes' for a path. Individual axis encoder readings had to be within a pre-defined error threshold value before the robot could move to the next node along the path.

Based on the premise above 50 adjacent nodes were selected at the centre section of Path 4. By comparing node values generated by the control program with actual node Cartesian positional data collected, an accurate determination of actual errors for each joint could be determined. This was achieved by only selecting values for comparison at a particular node point rather than at some arbitrary transitional point between nodes. The x, y and z coordinates collected from the data capture PC were converted back into encoder readings. For 50 nodes on Path 4 'original' system encoder error values of 3, 103 and 10 were recorded for the Theta, X and Z axes respectively, confirming the supposition that the X axis would be the most inaccurate.

The 'original' error membership function was narrow at ± 1.0 . According to the research by narrow membership functions produce a faster response time, although this can result in extended settling times, increased overshoot and oscillation [6]. It was apparent that any smaller membership function width applied when compared to the original error value was unsuccessful due to the extended settling time. Consequently as a result of the extended time required the error threshold value was not met for a specific node on a desired path resulting in the control system halting.

Conversely a larger membership function width increased the response time making link movement relatively slow, with steady state position not being reached or values moving out of the error threshold sampling range, again resulting in the control system halting.

Therefore, the simple incremental tests of increasing and decreasing error membership function width defined the boundaries for this function within the existing system parameters. Although control was achieved with a minimal increase and decrease in error membership function width when compared to the original value this resulted in an increase in axis error for all three axes.

These results gave some indication as to the performance of the robot control system but importantly showed that three axes could be controlled in real time with a variation in control system demands, whilst achieving results as low as $86\mu\text{m}$ and $93\mu\text{m}$ for repeatability and accuracy respectively.

X axis errors were attributed to the inherent mechanical system inaccuracies including stickion within the motor drive system and amplifier operating conditions. The amplifier for the X axis was tuned to operate at maximum current output levels dependent on the output from the D/A converter via the fuzzy engine. The output profile from the amplifier could be questionable at the extremes of operational output when demand from the motor was high for very small motor movements, this having a direct effect on joint resolution. Further improvements including inspection and servicing of the mechanical drives and upgrading the existing amplifier specification would help address X axis inaccuracies.

Both single and multi-axis testing showed that this error could not be reduced further without adding additional computational and hardware interface overheads to the existing system, a burden that the current system specification could not support.

The path tests for accuracy and repeatability were undertaken at full load of 5kg. The load would have certainly affected the accuracy of the robot but conversely the repeatability value would be independent of the load condition. Reference [7] states that repeatability is expressed in metric units with the value expressed for repeatability being smaller than the value for accuracy; experimental results and calculations carried out for this project verified this statement.

VII. ROBOT PERFORMANCE

Repeatability and accuracy tests were performed to give an indication of system performance whilst operating at the specified maximum original equipment load. Performing the various tests was used as a method to confirm the functionality and ability of the fuzzy control system to cope with the various test paths, whilst utilising the repeatability and accuracy values as a form of performance measure. The tests also served as a mechanism in assessing system performance due to the additional demands placed on the controller as a consequence of a variation in system overheads. The control system flowchart is shown in Figure 6.0.

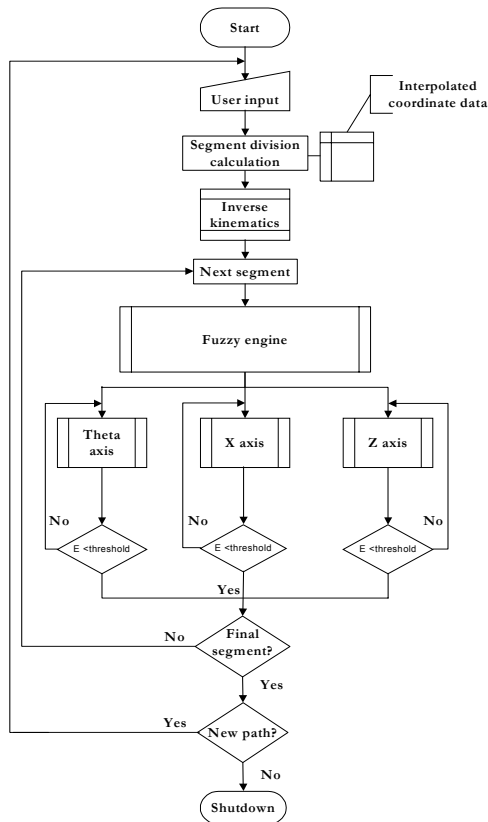


Figure 6.0: Control system flowchart

VIII. CONCLUSIONS

An industrial robot control system has been designed, developed and implemented utilising fuzzy logic to control three robot axes in real time. The choice of a fuzzy controller was based on a need to assess its robustness in operating over a wide range of working conditions. The basic fuzzy controller can offer certain advantages; one of which being that there is no requirement for detailed mathematical models of the system in order to formulate the appropriate control algorithms. In this application each axis of the robot may be tuned with its own set of control rules and scaled values.

However, some limitations still need to be addressed, including the determination of the rule base itself and its completeness, the ideal shape for the various fuzzy sets and methods for calibrating and testing the stability of the final system.

The use of 'basic' fuzzy engine and manual parameter tuning using efficient algorithms and efficient software coding has provided a novel approach to multi-axis fuzzy robot control. The results achieved with the existing fuzzy engine and hardware with its inherent limitations have provided exciting possibilities for further controller development based on existing fuzzy algorithms. Maintaining accuracy and

repeatability whilst increasing link velocity would certainly be attainable, possibly with only small software modifications. In addition, the software algorithms and associated program code, although written specifically for robot control, would be readily transferable to generic applications based on DC servo motor control.

By adopting a practical approach to the development of the fuzzy robot control system 'real world' problems, including those associated with electronic hardware interfacing, computer control and inherent robot system mechanical inaccuracies have been met and resolved. Linear path tests for accuracy and repeatability based on ISO 9283 (Manipulating Industrial Robots – Performance Criteria and Related Test Methods), gave an indication of the success of the three axis fuzzy control system, the tests completed for path accuracy and repeatability verifying that real time control of the three axis robot has been achieved whilst maintaining satisfactory robot performance.

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