Intelligent Coordinate Control over Cooperative Micro Robots for Nondestructive Testing of Large Steel Plates

S Sreedharan*, G Bezanov †

*, †*Embedded Systems Laboratory, Centre for Automated and Robotic NDT,*
London South Bank University, 103, borough Road, London, United Kingdom, SE1 0AA

Keywords: Micro-robot, Intelligent control, Steel plate, NDT

Abstract

Multiple, lightweight micro-robots configured to work in a cooperative environment are considered in many applications of Non destructive testing (NDT) where they replace a single large robotic inspection system. Their main advantages over the single larger system are that they are more mobile, do not require a heavy umbilical cord and can be programmed to work in a multi-robot environment using an intelligent software agent.

Effective intelligent control of these robots is very challenging because it has to be adaptable to suit different application needs. This paper reports the development of an intelligent co-ordinate control over mobile micro-robots to perform multitasking for non-destructive testing of steel plates. The knowledge based agent uses the forward chaining inference engine that enables control of robot movements on a steel plate. The path for a rectangular shaped work area has been generated by developing an algorithm that follows required robot movements for steel plate inspection. An algorithm for the division of work area for cooperating robots has also been developed. The algorithms are tested in MATLAB simulation before testing in real-time. The results show considerable improvements for the micro robots over a single large inspection robot.

1 Introduction

Conventional methods of inspecting steel plates favour the use of a vehicle fitted with NDT (Non-Destructive Testing) equipment, which is guided manually in order to inspect the steel plate for cracks and other anomalies [1]. Automated systems such as developed at the Centre for Automated and Robotic NDT (CART)'s Steel Plate Inspection Vehicle, provide a more efficient solution [2,3]. The miniaturization of this solution has been achieved by implementing two changes.

i) Reduction in the complexity of the automated inspection system:

The complexity of the automated system for the inspection technique can be reduced by replacing the 16 probes arrangement Pulse-Echo method with the emerging 2 probe ultrasonic method, which is the Time of Flight Diffraction method (TOFD). Thus, the design of the robotic vehicle will accommodate the NDT hardware on board and the NDT data will be transferred to a nearby computer for processing via radio modems which will also aid remote robot control.

ii) Elimination of the heavy umbilical cord between the robot and the control system: Using wireless data transmission and control the bulk and complexity of the robot inspection system can be reduced. Thus, the robotic vehicle will be less complex and can be miniaturized. This leads to the development of miniature standalone robotic systems.

To control the miniature robots on a steel plate, a sensory environment has been developed by the aid of a camera. The camera monitors the steel plate activities from a height of 3 meters. The digital image processing of the camera images based on Visual Basic identifies the robots and borders on the steel plate. The control software sends the necessary data to the robotic vehicle via remote control. In this approach, the robotic vehicle will know the status of its position on the steel plate as well as the controls that it has to perform. This information is needed for the robot to do the inspection and also for developing intelligent control.

The inspection robot needs to scan the steel plate irrespective of its shapes. T**he first objective** of the intelligent agent is to develop an algorithm to control the movements of a single robot on a rectangular work area.

The **second objective** is to inspect any dimensional rectangular work area by using several micro-robots with co-operative inspection.

2. Inspection Technique

The non-destructive testing (NDT) of steel plates is performed to detect defects. Ultrasound techniques of Pulse-Echo and Time of flight diffraction (TOFD) are proven methods of NDT inspection [4]. For inspection of large steel plates, TOFD is often the preferred choice. [5,6,7,8] The coverage rates attainable are restricted only by the practicalities of scanning and inspection rates of 100 - 150mm/sec are achievable by using manual deployment methods. Higher rates of coverage can be achieved when automated scanning is used [2,3,5,9]. However, the inspection of defects near edges by TOFD may contain noise and for near edge defect detection an angled pulse-echo probe can be included [10,11]. These findings proposed a new 'inspection unit' which is less complex and can be fitted on micro-robot as shown in figure-1. The proposed inspection unit is assumed to have 100% scan area coverage however further research is needed in this area.

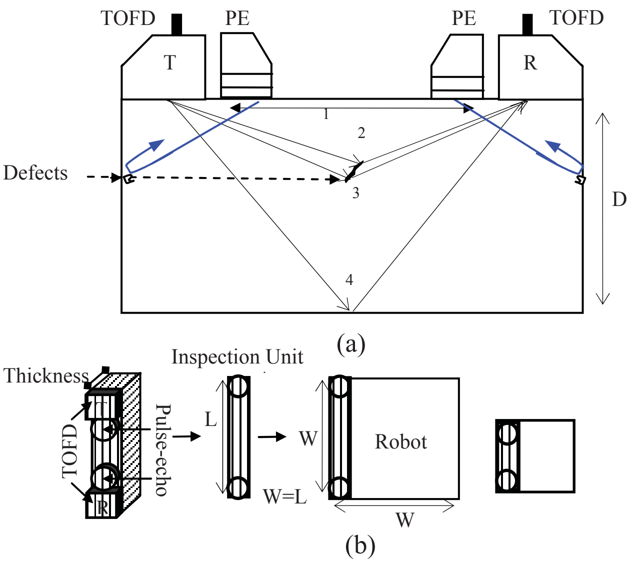

Figure .1. (a) Inspection unit contains TOFD transducers and couple of pulse-echo transducers. (b) The unit is fitted on rear side of the robot.

3. Robotic Mechanism for Inspection

For steel-plate inspection, research has been carried out in the field of wheeled mobile robotic mechanisms and in particular the differential drive (DD) mechanism is found to be the most suitable for the inspection. Recent research by Balkcom and Mason bounded the speed of the DD and minimized the total time that it takes to travel from initial configuration 'q_I' to a goal configuration 'q_G' [12].
The Balkcom-Mason drive (BMD) relies on the Balkcom-Mason optimal curves (BMC) [13] to define inspection paths on the steel plate. The BMC is used to calculate the total cost of the inspection trajectory and includes both linear and rotational motion of the inspection robot.

3.1 Path costing

The paths of micro-robots for inspection can be viewed as several goals set to follow the BMC. There are a total of nine symmetry classes (A, B, C, to I) reported for BMC [13]. From these, three symmetry classes, namely classes B, D and F describe the inspection movements. These three symmetry classes form BMD's time optimal trajectories. From Balkcom and Mason [14] the cost function for these trajectories can be described as follows:

$$CF_{tst} = (b \times (|\theta_s| + |\theta_g|)) + l \qquad (1)$$

-where, 'b'-half of the (square shaped) robot width i.e., 'w/2' and 'l'- the path length. Equation 1 does not minimise rotational cost and the micro robot can rotate either clockwise or counter clock wise to point to the goal state at 'θ_s' or at 'θ_g'. Research found that for the inspection robot, where $\theta_s = \theta_g = \pi/2$ the only possible movements are those depicted in figure 3, the minimum rotational cost will always be '$|\theta_s|+|\theta_g|=\pi$'. Accordingly, and provided that the inspection robot follows BMCs, for any path planning techniques the total cost estimation can be written as follows:

$$C_{total} = b(n * \pi / 2) + \sum_{i=1}^{m} l_i \qquad (2)$$

-where C_{total} is the total cost to inspect steel plate, 'n' is the total number of rotations, sigma l_i is the total path length for the robot.

4. Motion Planning

Research in Semi-Autonomous Navigation (SAN) [15,16] which is a deterministic offline path planning technique, indicates that it is a viable solution for the inspection robots. If an USB camera is fitted at a reasonable distance on top of the micro-robots and the steel plate work area (analogues to SAN) then, a suitable 'sensory environment' is obtained for the inspection in order to control the micro-robots.
For motion planning, research identified two basic movement plans within the mesh survey strategy, which are; directed-parallel method (sweep) – DPM and contour-parallel method (Lawnmower spiral) – CPM [17,18,19]. From equation 2, research found that for multi-structures, the higher number of rotations cause the CPM to have higher inspection cost compared to DPM as depicted in Figure 2. Also, comparison of the costs of inspecting steel plates of rectangular shapes to those of any shaped work area, the directed-parallel method (DPM) offline path planning technique is found to be more cost-effective.

To generate inspection paths for both CPM and DPM methods, two edges of the configuration space and Voronoi diagram are used [20,21]. In order to develop an algorithm for calculating the DPM coordinates for a rectangular work area, we use continuous coordinates for travelling paths in '$\Re^2$'.

The paths of a DPM method for a rectangular shaped work area can be represented in the shape of a square wave as shown in Figure 3. The number of these –

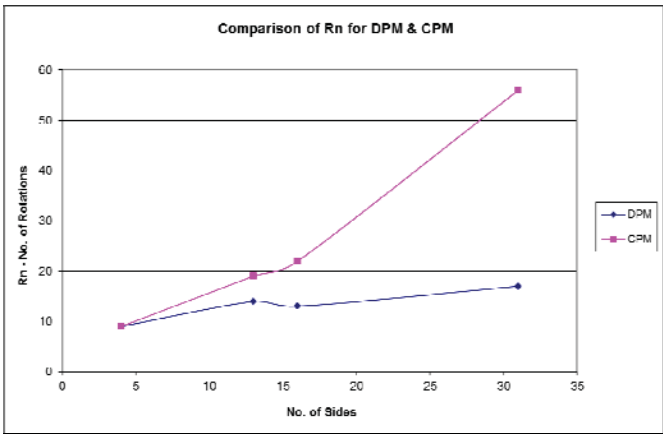

Figure 2. Number of rotations 'Rn' for DPM and CPM with the multi-shapes having different number of sides.

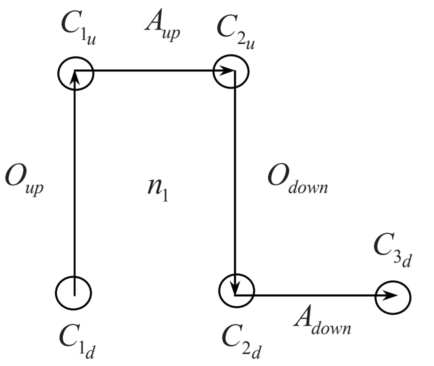

Figure 3. The square wave representation of the DPM cycle having four paths and its five cycle points for a rectangular work area.

-square wave shaped paths can be represented as frequency 'f'. Accordingly, we derive an equation to find the DPM coordinate values (cycle point) in the form '(x, y)' as follows:

$$\overset{fd}{\underset{1}{f}}(\ n_{1,2,,,f_d}\ [C_{(1,2)_{d,u},3_d}\ (x, y)] \quad =$$

$$x = (((4n_{1,2,,,f_q}) - 3) + (2 * (C_{(1,2)_{d,u},3_d} - 1))) * r_w / 2,$$

$$y = (w_y * C_{(d0\,,\,u1)}) + (r_W * NOT(C_{(d0\,,\,u1)})) - (r_w / 2)) \qquad (3)$$

- where '$C_{(1,2)_{d,u},3_d}$' describes the coordinates of the cycle points as depicted in figure 3 having values '$C_{1_d} = C_{1_u} = 1$, $C_{2_d} = C_{2_u} = 2$ and $C_{3_d} = 3$' in the n^{th} cycle which is '$n_{1,2,,,f_d}$' having values '1 to f_q' for the calculation of abscissa coordinate which is the 'x' coordinate of equation 3. For the 'y' coordinate, 'w_y' is the ordinate length of the work area having product values by the cycle point '$C_{(d0\,,\,u1)}$' such that at cycle point position 'down' '$C_{d0} = 0$' and cycle point position 'up' $C_{u1} = 1$. And '$NOT(C_{(d0\,,\,u1)})$' are having opposite values for the cycle point '$C_{(d0\,,\,u1)}$'. For example, an ordinate length having 'down' cycle point 'C_{2_d}' will have the cycle point value '$C_{(d0\,,\,u1)} = C_{d0} = 0$'. Then for the cycle point 'C_{2_d}', '$NOT(C_{(d0\,,\,u1)})$' will have value NOT $C_{d0} = 1$. Accordingly,

$$C_{u1} = 1,\ \ NOT\ (C_{u1}) = 0\ \ \&\ C_{d0} = 0,\ \ NOT\ (C_{d0}) = 1$$

Rearranging;

$$C_{u1} = NOT\ (C_{d0}) = 1\ \&\ C_{d0} = NOT\ (C_{u1}) = 0 \qquad (4)$$

The equation 3, called the DPM algorithm, can calculate any cycle point coordinates in the form '(x, y)' for a rectangular work area. In order to calculate the coordinate values of abscissa or ordinate path, only the frequency and the cycle point values are required for equation 3. This satisfies the **first objective** of the intelligent control system as explained earlier.

Research has shown that a minimum of two paths are required for the micro-robot to inspect a rectangular shaped work area in which one path length should be at least twice the width of the robot. [29]

For the cooperative inspection, the micro-robots need to share the inspection task equally which is achieved by the off-line path planning technique. To achieve this, the total number of paths is divided by the number of robots. Research found that equal division of 'number of paths' to the robots produces different path lengths. The result is a left-over number of paths. Nevertheless, the maximum difference between robot's path length will not exceed the ordinate path length 'O_L'.

Further analysis reveals that the last robot can carry out the rest of the path length inspection because the left over number of paths are not sufficient to distribute equally to all robots. Research also reveals that to improve the micro-robot's multitasking efficiency when larger work area is considered division of 'ordinate paths' has to be performed. This is because, for larger work area the 'robot width' will be negligible compared to its 'ordinate path length'.

Cooperation of robots also maintains discipline in multitasking to avoid collisions. Collision avoidance is supervised by the control computer and research reveals that to avoid collision, the robots in a given work area require a minimum 'six numbers of paths'.

5. Intelligent Control for the Inspection

Research identified that Knowledge-based Agent (KBA) approach for the control of inspection robots can improve the effectiveness and speed of inspection tasks. Furthermore, if the percept inputs for the KBA only contain the attained coordinate data, the complexity in the percept inputs is minimized.

Research in the field of knowledge representation reveals that first-order logic (FOL) which falls under 'predicate logic' can fully represents the DPM domain [22]. The effective procedures for answering questions posed in 'knowledge engineering' for first-order logic (FOL) has identified 'forward chaining' as the viable inference mechanism for DPM [23,24]. Research also shows that reasoning with forward chaining is more efficient than 'resolution theorem' proving [25].

In order to use inference with FOL, we use first-order definite clauses (FODCs) which are horn clauses with exactly one positive literal. These clauses are suitable for use with 'Generalised Modus Pones' (GMP) inference rule [26,27]. The Modus Ponens can be seen as a 'sound' inference rule [28] and since GMP follows Modus Ponens therefore GMP is also a sound inference rule.

The simulation of KBA is performed in MATLAB, and Excel is used to calculate DPM algorithms, DPM path generation, and division of paths for micro-robots. The parameters considered for the DPM algorithm calculation in Excel are converted to first-order definite classes (FODCs) for both MATLAB simulation and the real-time VB platform. All necessary facts for the DPM can be represented in FODCs. However, to avoid complexity, some rules are kept in prepositional logic implications (PLI) where the consequent of the implication has many literals. This confirms that the

KBA must combine both 'declarative' and 'procedural' elements in its design [25].

In MATLAB simulation of the KBA, it has been shown that the identified inference algorithm, namely: 'Incremental FOL-FC-Ask' – Incremental First Order Logic – Forward Chaining – Ask (IFFA)' [25] successfully executes in two iterations. The first iteration has two phases in which the primary phase calculates the DPM coordinates. For this IFFA algorithm, the primary phase TELLs the KB the user static data inputs via the user button action (Figure 6) for the 'query' input 'α'. The secondary phase executes the actions for the micro-robots to complete the first cycle.

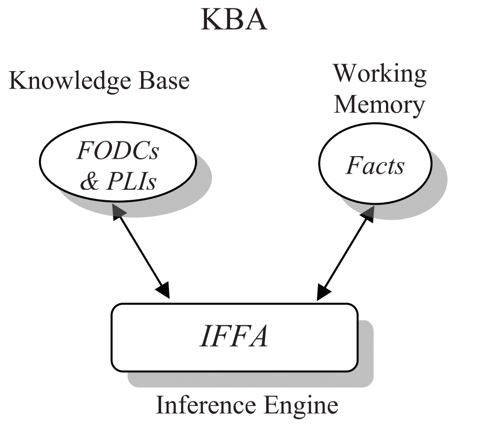

Figure 4. Knowledge-based Agent (KBA) Simulation infrastructure for DPM

During the second iteration the unification action '$\phi \leftarrow$ Unify (q', α)' is performed. This process is repeated until the query is answered, that is to reach the negative last abscissa path (NLAP). This means the micro-robot has reached its destination and the IFFA algorithm ends with text outputs to GUI as the result of the query.
Figure 4 shows the KBA simulation infrastructure for DPM movement. Figure 5 represents the MATLAB simulation code for the flow of IFFA incremental action.

```
While NLAP = = 0,
        Do DPM Functions
        [DPM] = NLAP ( ); (NLAP =1)
            if (NLAP = =1),
                Robotcod_finishcod = 1;
            else
                if (NLAP_C = =2),
                    NLAP = 1;
                end
 end
```

Figure 5. The IFFA algorithm in MATLAB codes.

6. Simulation of the Intelligent Control

MATLAB simulation reveals KBA's abilities to direct robot movements for inspection of a work area having fractional lengths and lengths with decimal points. The simulation also includes warnings to the user if a defined problem occurs, including decision on minimum work area requirements and warnings such as to increase the work area dimension, etc.

Results from experiments with a single robot in MATLAB simulation as depicted in table 1 confirm that work area having longer sides will have fewer rotations for the DPM movement and therefore lower cost of inspection.

Table 1. MATLAB simulation conducted for same rectangular area having different height and width.

Height (cms)	Width (cms)	Area (cms^2)	Time (secs)	(pi/2) number of rotations
100	100	10000	22	19
125	80	10000	17	15
200	50	10000	13	9
250	40	10000	11	7
500	20	10000	8	3
1000	10	10000	6	1

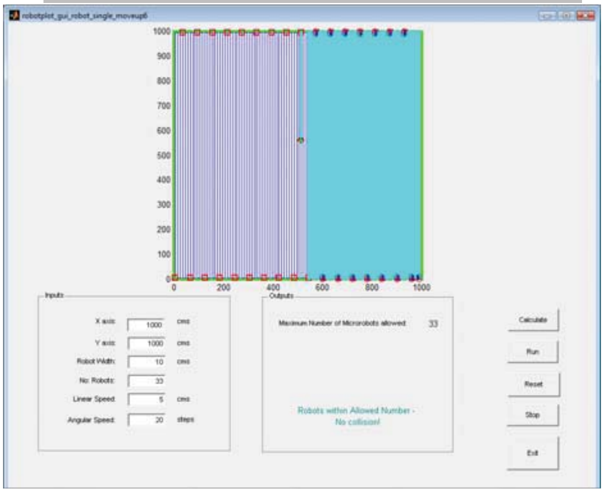

Figure 6. MATLAB GUI Window showing the micro-robots doing DPM. Dimension: Wy= Wx=1000 cms and rw =10, Rn = 33.

MATLAB simulation results show that the IFFA incremental 'forward chaining' mechanisms provide cost-effective inspection by cooperative micro-robots.
The cooperative inspection by 33 micro-robots for a given work area of 1000 cm^2 is depicted in Figure 6. This satisfies the **second objective** of the intelligent control system defined earlier.

7. Real-time testing of the Intelligent Control

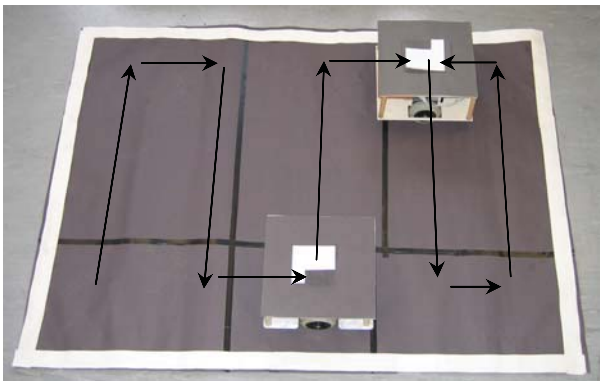

Figure 7. The real-time cooperative micro-robot's DPM movements showing the prototypes reached destination coordinates and manually drawn DPM paths.

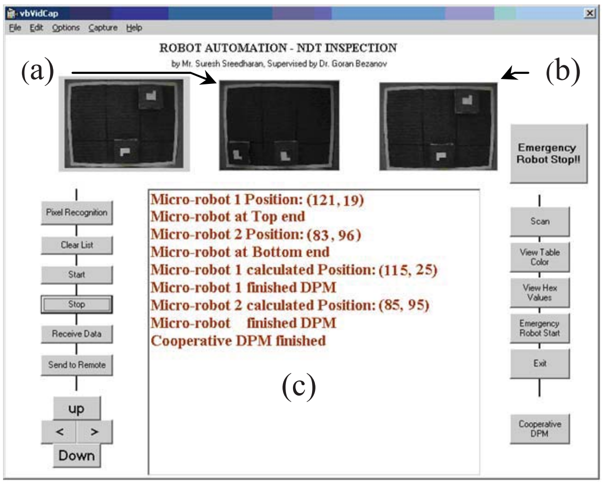

Figure 8. The VB GUI a) The picture box showing the micro-robots' initial coordinates. b) The micro-robots reached destination. c) Micro-robots' calculated and current coordinates and reachability information.

Two micro-robot prototypes were developed and used to test the KBA algorithm for performing the cooperative DPM movements as simulated in MATLAB. The prototypes have two-way wireless commutation to send coordinate values to the robots. Real-time tests reveal the capability of the camera sensory environment (CSE) in Visual Basic (VB) platform to detect robots with reference to the borders of the inspection area by the detection algorithm.

Figure 7 shows the placement of the two micro-robots for real-time test and Figure 8 shows the VB GUI output window for the control of the micro-robots.

Results show good support from the MATLAB simulation to develop the KBA for the real-time experiments with the VB platform. Comparing the calculated DPM coordinates and attainted coordinates from camera pixel data, the error build-up until the end of DPM movements are within the six pixel tolerance as depicted in table 2.

Table 2. The DPM coordinate values of the micro-robot's for the work area given in figure 6. 'Differ (error)' is the difference between calculated and attained coordinates values in the form (x, y).

No	Pos	Micro-robot 2 coordinate values				
		Cals DPM	From Camera	Differ (error)	After pi/2 Rotation	Differ (error)
1	1-D1	(85, 95)	(88, 97)	(3, 2)		
2	1-U1	(85, 25)	(82, 27)	(-3, 2)	(77, 27)	(-8, 2)
3	1-U2	(115, 25)	(106, 25)	(-9, 0)	(120, 20)	(5, -5)
4	1-D2	(115, 95)	(121, 92)	(6, -3)	(119, 91)	(4, -4)
5	2-D1	(135, 95)	(138, 93)	(3, -2)	(137, 89)	(2, -6)
6	2-U1	(135, 25)	(139, 20)	(4, -5)	(138, 22)	(3, -3)
7	1-U2	(115, 25)	(121, 19)	(6, -6)		

Research also suggests that for steady lighting conditions, a high performance camera should be in place to obtain steady pixel counts. Earlier research identified Bayesian estimation to correct the pixel counts for varying lighting conditions.

8. Cost comparison

A comparison of the cost of inspection in terms of inspection length is performed for the CART's previous inspection robot (CIR) to the developed inspection robot prototype – (IRP) micro-robot. For the work area given in figure 7, results show that the cost of path in CIR is nearly 3.4 times higher than that of IRP. Results also show that when the robot's initial direction is along the longer side of the work area, CIR's cost increased by 1.2% whereas for IRP, under similar conditions, a 17% reduction in cost is recorded. This reduction in cost is mainly due to the 100% inspection capability of IRP unit compared to CIR (using 16-pulse-echo probes) and also the cost effective DPM movements.

For the **second objective,** research identified that the cost of inspection for the cooperative micro-robots is the cost of the last micro-robot. This is due to cooperative inspection in which all micro-robots start at the same time and only the last micro-robot carries out inspection for its allocated paths and the left over paths. This means, that for equal distribution of number of paths, last micro-robot has more paths consequently, takes more time to finish inspection while others finish [29]. The cost of CIR is calculated considering its paths only because cost of rotation was negligible due to its design considerations [2]. Comparing the cost of IRPs with CIR's cost reveals that the cost of IRPs is further reduced by a factor 1/5.33. Accordingly, the superior effectiveness of the real-time cooperative micro-robots' DPM movements by KBA is demonstrated. Results show that the IFFA inference algorithm is 'complete' and cost of inspection is reduced more than five times compared to CIR. The DPM offline path planning technique is shown to be a viable method to reduce the complexity of the inspection vehicle.

Further cost reduction for IRP is achieved if sufficient paths are allocated to the number of micro-robots'. [29] Results show that the cooperative micro-robot's cost (IRP_{cost}) can be approximately estimated from the given cost of CIR (CIR_{cost}) as follows:

$$IRP_{cost} \approx 2 * CIR_{cost} / R_n \quad (4)$$

-where Rn is the number of micro-robots,

However, this relation is not true for a smaller work area. Because if $R_n = 2$, then $IRP_{cost} = CIR_{cost}$, which is not true. The equation needs to be refined further to obtain a closer approximation for smaller work areas.

9. Conclusion

Simulation tests reveal successful completion of the IFFA incremental forward chaining inference for a single robot and cooperative micro-robots to perform the DPM of any dimensional rectangular workspace. Accordingly, a 'sound' inference algorithm is developed for the closed-ended KBA

The real-time cooperative micro-robots' DPM movements by KBA as well as the developed CSE is demonstrated successfully with the two built prototype micro-robots. The IFFA algorithm derives any required FODCs and PLIs entailed sentences to perform the DPM movements [29]. Therefore, the IFFA inference algorithm is also 'complete' for successful workspace inspection. Real-time experiments with the built IRPs reveal that the cost is reduced more than five times compared to CIR. The DPM offline path planning technique is a viable method to reduce the complexity of the inspection vehicle which supports the introduction of cooperative micro-robots for large steel plate inspection.

References

1. "Steel plate inspection trolleys". Insight NDT Equipment Ltd, technical paper no: UT004, 2006.
2. Rakocevic,M., Wang,X. "Automated Inspection System for NDT of Steel Plates," Published by the British Institute of Non-Destructive Testing, Sept. 1998.
3. Sreedharan, S. et al. "Developing An Embedded Control System to Miniaturize Automatic NDT inspection of Steel Plates", UPEC 2001, *The 36th Universities Power Engineering Conference*, Sept. 2001.
4. Bridge,B. et al. "Non-Destructive Testing, An Eastern-Western European Perspective," Published by The Institute of Non-Destructive Testing, Sept. 1998, pp. 16-19.
5. Browne, B. "Time of flight diffraction, Its Limitations - Actual & Perceived", NDTnet, Vol.2 No.09, 1997.
6. Mondal, S. "An overview TOFD method and its Mathematical Model", NDT.net – Vol.5 No. 04, April 2000.
7. Rebecca Wuellner and José A. Pincheira Nondestructive. "Testing of Steel Bridge Members Using the Time of Flight Diffraction Method", Department of Civil and Environmental Engineering University of Wisconsin-Madison, 2003.
8. Zahran, O., Al-Nuaimy, W. "Automatic Classification of Defects in Time-of-flight-Diffraction", Department of Electrical Engineering & Electronics, The University of Liverpool, 2004.
9. "The British TOFD standard BS 7706 Guide to Calibration and setting-up of the Ultrasonic Time of Flight diffraction (TOFD) technique for defect detection, location and sizing of flaws", NDTnet, September 1997, Vol.2 No.09.
10. Khalid, A. et al. "The Centre for automated and Robotic NDT at south Bank university (UK): Development of Novel Climbing Robot Technology for Non-destructive testing in Hazardous Environment". Non-Destructive Testing An Eastern-Western European Perspective, The British Institute of Non-Destructive Testing, 1998.
11. Ginzel, E., Lozev, M.G. "Code Review: Time-of-Flight Diffraction and Pulse Echo Line Scanning Presented in the Seminar on Automated Ultrasonic Inspection of Welds Using Time-of-Flight Diffraction and Pulse Echo Line Scanning at Edison Welding Institute in Materials Research Institute", NDE Technology Team, NDT.net, February 2001, Vol. 6 No. 2.
12. Balkcom, D.J.; Mason, M.T. "Extremal trajectories for bounded velocity mobile robots", International Conference on Robotics and Automation, Proceedings ICRA 02". IEEE Volume 2, vol.2, 2002 pp.1747 – 1752.
13. Balkcom, D.J., Mason, M.T. "Time optimal trajectories for bounded velocity differential drive Robots", Proceedings of the 2000 IEEE, International Conference on Robotics & Automation, CA, 2000.
14. Balkcom, D., Mason, M. "Geometric construction of time optimal trajectories for differential drive robots", Proceedings of the Workshop on the Algorithmic Foundations of Robotics (WAFR "00), 2000.
15. Andreou, P., Charalambides, A. "Exploring Mars Using Intelligent Robots". A web-based article, Internet: http://www.doc.ic.ac.uk/~nd/ surprise_95/journal/vol4/pma/report.html#Introduction [1995].
16. Wilcox, B. et al. "Robotic vehicles for planetary exploration", Proceedings of the International Conference on Robotics and automation.1992.
17. Kurabayashi, D. et al. "Cooperative sweeping by multiple mobile robots", IEEE Int. Conf. on Robotics & Automation, vol. 2, 1996, pp.1744 - 1749.
18. Arai, T. et al. "Motion Planning for Cooperative Sweeping with Relocating Obstacles", IEEE International Conference on Systems, Man, and Cybernetics, vol. 2., 1996, pp. 1513-1518.
19. Luo, C., Yang, S.X. "A real-time cooperative sweeping strategy for multiple cleaning robots", Proceedings of the 2002 IEEE International Symposium on, Oct. 2002, pp. 660-665.
20. Kurabayashi, D. et al. "An algorithm of dividing a work area to multiple mobile robots", IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, vol. 2, 1995, pp.286 - 291.
21. Law, J. "Analysis of Multi-Robot Cooperation using Voronoi Diagrams", the Open University Milton Keynes, MK7 6AA, UK, 2005.
22. Wang, K., Yuan, L.Y. "First-order logic characterization of program properties Knowledge and Data Engineering," IEEE Transactions on, vol. 6, Issue 4, 1994.
23. Thomas, G., Paul, R.C. "Knowledge Engineering Tools at the Architecture Level," Proceedings of the 10th International Joint Conference on Artificial Intelligence. Milan, Italy, August 1987.
24. Poole, D.L. et al. "THEORIST: A Logical Reasoning System for Defaults and Diagnosis Technical Report, Department of Computer Science, University of Waterloo, Waterloo, Canada, 1985.
25. Russell, S., Norvig, P. Artificial Intelligence: A Modern Approach, 2nd Ed., Prentice Hall, 2003.
26. Dubois, D., Prade, H. "Generalized Modus Ponens under sup-min composition – A theory study", Approximate Reasoning in Expert System, 1985, pp. 217-232.
27. Giuseppe D.B., Maurizio, L. "Deductive Entity Relationship Modelling", IEEE transactions on knowledge and Engineering, vol. 5, NO. 3., 1993.
28. Thomas, W., Brian, S. "Modus Ponens, Modus Tollens, and Fuzzy Relations in Goal Directed Inference", Proceedings of IEEE Int'l Conference on Systems, Man, & Cybernetics, 1987.
29. Sreedharan, S. "Control System Analysis and Design of Co-operative Mobile Micro-Robotic Mechanisms Used for Remote and Hazardous NDT", PhD Thesis, London South Bank University, 2012.