Enabling Methodologies for Optimal Coverage by Multiple Autonomous Industrial Robots

by

Mahdi Hassan

A thesis submitted in partial fulfillment for the degree of Doctor of Philosophy

in the
Faculty of Engineering and Information Technology
Centre for Autonomous Systems

February 2018
Declaration of Original Authorship

I, Mahdi Hassan, certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This research is supported by an Australian Government Research Training Program Scholarship.

Signature of Student: __________________________

Date: 23/02/2018
Acknowledgements

Firstly, I would like to thank my principal doctoral supervisor, Prof. Dikai Liu, for providing me the opportunity to carry out this research work and to study in the field of robotics which is of my interest and passion. I appreciate his knowledge and expertise in the field, and I am truly grateful to him for his support and encouragement, and for patiently guiding me through my research.

I thank my co-supervisor, Dr. Gavin Paul, for motivating me with my research through his kind words. I am thankful to him for all his help, for showing interest in my research, and for providing me with valuable advice and reviews to improve the quality of my work.

My gratitude also goes to all project members and in particular Prof. Gamini Dissanayake, Asoc. Prof. Shoudong Huang, Dr. Andrew To, and Mr. Teng Zhang for their valuable discussions and suggestions. A big thanks to all other members of CAS for making the research environment fun and exciting, and for helping out when possible. Many thanks to my friends in the faculty of engineering, particularly Mr. Raphael Falque, Mr. Yuhan Huang, and Mr. Nizar Al-Muhsen for their friendship and support. I would also like to thank UTS, the project partner (SABRE Autonomous Solutions), and CAS for fundings and their interest in my research.

I would like to express my special gratitude to my parents for motivating me to pursue my research. A special thank to my wife Yousra for believing in me, understanding the busy nature of PhD studies and patiently helping with simplifying my life while I undertake my research.
Abstract

Unlike traditional industrial robots which are purpose-built for a particular repetitive application, Autonomous Industrial Robots (AIRs) are adaptable to new operating conditions or environments. An AIR is an industrial robot, with or without a mobile platform, that has the intelligence needed to operate autonomously in a complex and unstructured environment. This intelligence includes aspects such as self-awareness, environmental awareness, and collision avoidance. In this thesis, research is focused on developing methodologies that enable multiple AIRs to perform complete coverage tasks on objects that can have complex geometric shapes while aiming to achieve optimal team objectives.

For the AIRs to achieve optimal complete coverage for tasks such as grit-blasting and spray painting several problems need to be addressed. One problem is to partition and allocate the surface areas that multiple AIRs can reach. Another problem is to find a set of appropriate base placements for each AIR and to determine the visiting sequence of the base placements such that complete coverage is obtained. Uncertainties in base placements, due to sensing and localization errors, need to be accounted for if necessary. Coverage path planning, i.e. generating the AIRs’ end-effector path, is another problem that needs to be addressed. Coverage path planning needs to be adaptable with respect to dynamic obstacles and unexpected changes. In solving these problems, it is vital for the AIRs to optimize the team’s objectives while accounting for relevant constraints.

This research develops new methodologies to address the above problems, including (1) a Voronoi partitioning based approach for simultaneous area partitioning and allocation utilizing Voronoi partitioning and multi-objective optimization; (2) optimization-based methods for multi-AIR base placements with uncertainties; and (3) a prey-predator behavior-based algorithm for adaptive and efficient real-time coverage path planning, which accounts for stationary or dynamic obstacles and unexpected changes in the coverage area.

Real-world and simulated experiments have been carried out to verify the proposed methodologies. Various comparative studies are presented against existing methods. The results show that the proposed methodologies enable effective and efficient complete coverage by the AIRs.
Contents

Declaration of Original Authorship ............................................................. i

Acknowledgements ......................................................................................... ii

Abstract ........................................................................................................... iii

List of Figures .................................................................................................... viii

List of Tables .................................................................................................... xi

Abbreviations ................................................................................................... xii

Nomenclature ................................................................................................... xiii

Glossary of Terms ............................................................................................ xxi

1 Introduction .................................................................................................. 1
  1.1 Motivation .................................................................................................. 2
  1.2 Scope ......................................................................................................... 4
  1.3 An Example Application .......................................................................... 6
  1.4 Contributions ............................................................................................ 8
  1.5 Related Publications ............................................................................... 10
  1.6 Thesis Outline .......................................................................................... 11

2 Review of Related Work .............................................................................. 14
  2.1 Complete Coverage of Flat Surfaces by a Single Robot ......................... 15
  2.2 Complete Coverage by Multiple Robots ............................................... 16
  2.3 Complete Coverage Using UAVs and AUVs ........................................... 18
  2.4 Complete Coverage Using Industrial Robots ........................................ 21
  2.5 Complete Coverage Using Autonomous Industrial Robots .................. 22
  2.6 Adaptive Coverage Problem with Respect to Change and Uncertainties .. 23
  2.7 Base Placement and Area Partitioning for Complete Coverage ............. 26
  2.7.1 Base Placement Optimization ............................................................ 26
3 A Voronoi Partitioning Based Approach for Simultaneous Area Partitioning and Allocation

3.1 Problem Definition .............................................. 32
3.2 Methodology .................................................. 37
   3.2.1 The APA Approach ........................................ 37
   3.2.2 Mathematical Model ...................................... 38
      3.2.2.1 Design Variables .................................. 38
      3.2.2.2 Objective Functions ................................ 39
         Objective 1 - Minimal Makespan: ....................... 39
         Objective 2 - Minimal Closeness of the Allocated Areas to
         the Specific Areas: ...................................... 41
         Objective 3 - Minimal Torque: ........................ 42
         Objective 4 - Maximal Manipulability Measure: ........ 43
3.3 Case Studies and Results ...................................... 44
   3.3.1 Procedure for Calculating the Objective Functions ........ 45
   3.3.2 Case Study 1: Three AIRs with Different Capabilities to Grit-blast
      a Flat Plate ................................................. 47
      Convergence and consistency: ............................ 49
      Search space and scalability: ............................. 49
   3.3.3 Case Study 2: Comparing the APA Approach to the Pattern-Based
      GA Approach ................................................ 50
   3.3.4 Case Study 3: Two AIRs to Grit-blast a Flat Plate in the Presence
      of an Obstacle ................................................. 52
   3.3.5 Case Study 4: Two AIRs Spray Painting Three Separated (Unconnected)
      Objects ...................................................... 54
      Trade-off between objectives: ............................ 57
      Convergence and consistency: .............................. 57
   3.3.6 Case Study 5: Demonstration of a Method to Fix Missing Sections
      when More than Two AIRs are Deployed ................... 59
   3.3.7 Case Study 6: Four AIRs with Different Overlapped Areas ........ 62
   3.3.8 Case Study 7: Two AIRs Used to Grit-blast a Small Area of a Steel
      Bridge .......................................................... 63
   3.3.9 Case Study 8: Two AIRs Used to Grit-blast a Boxlike Steel Structure 65
3.4 Discussion ...................................................... 67
3.5 Conclusions ................................................... 68

4 An Optimization-Based Method to Multi-AIR Base Placement 69
4.1 Problem Definition .............................................. 70
4.2 Methodology ................................................... 72
   4.2.1 The OMBP Method ......................................... 72
   4.2.2 Mathematical Model ...................................... 74
      4.2.2.1 Design Variables .................................. 74
4.2.2.2 Objective Functions .............................................. 75
   Objective 1 - Maximal Coverage: ................................... 75
   Objective 2 - Minimal Makespan: .................................. 77
   Objective 3 - Maximal Manipulability Measure: .............. 79
   Objective 4 - Minimal Torque: .................................... 80
4.2.2.3 Constraint Functions ........................................... 82
   Constraint 1 - Distance Between Any Two AIRs: ............. 82
   Constraint 2 - Distance to Obstacles: ......................... 82
4.2.3 Implementation of a Multi-objective Optimization Algorithm ... 83
   4.2.3.1 Chromosome Representation ............................. 85
   4.2.3.2 Crossover Operator ...................................... 87
   4.2.3.3 Mutation Operator ...................................... 88
4.3 Case Studies and Results ............................................ 89
   4.3.1 Procedure for Calculating the Objective Functions .... 91
   4.3.2 Case Study 1: Three AIRs Grit-blasting Three Objects .. 94
   4.3.3 Case Study 2: Three AIRs Applied in a Steel Bridge Maintenance Environment ................................. 96
   4.3.4 Case Study 3: Solution Quality and Consistency .......... 98
   4.3.5 Case Study 4: Two AIRs Perform Grit-blasting on a Vehicle ... 101
4.4 Discussion .............................................................. 105
4.5 Conclusions ............................................................. 106

5 A Stochastic Optimization-Based Method to Multi-AIR Base Placement for Complete Coverage Under Uncertainties 107
5.1 Problem Definition ..................................................... 108
5.2 Methodology ............................................................ 109
   5.2.1 The Stochastic-OMB Method .................................. 109
   5.2.2 Mathematical Model .......................................... 111
      5.2.2.1 Design Variables .................................... 111
      5.2.2.2 Objective Functions .................................. 111
      Objective 1 - Maximal Coverage: ............................ 111
      Objective 2 - Minimal Makespan: ............................ 113
   5.2.2.3 Constraint Functions (Distance Between Any Two AIRs) 114
   5.2.3 Multi-objective Stochastic Optimization Approach ........ 114
5.3 Case Studies and Results ............................................. 117
   5.3.1 Case Study 1: Two AIRs Grit-blasting a Vehicle’s Surfaces 117
      5.3.1.1 Checking Solution Consistency ........................ 118
      5.3.1.2 Comparing Hybrid GA-SA with NSGA-II ............. 119
      5.3.1.3 Testing for Various Levels of Uncertainties ......... 119
   5.3.2 Case Study 2: Three AIRs with Different Capabilities Grit-blasting a Complex Object .............................. 120
      5.3.2.1 Testing for Various Levels of Uncertainties ........ 121
5.4 Discussion .............................................................. 121
5.5 Conclusions ............................................................. 122
# List of Figures

1.1 Two mobile AIRs performing grit-blasting on three objects. .......................... 2
1.2 An abstract illustration of a process for conducting a complete coverage task using multiple AIRs. ......................................................... 4
1.3 Target representation of a vehicle’s surfaces from a point cloud is used for two AIRs to perform a complete coverage task. ................................. 7

3.1 The overlapped areas of two AIRs that have different tool coverage size are shown. ................................................................. 31
3.2 Overlapped and specific areas as well as the final paths associated with two AIRs which will be used to grit-blast or spray paint an I-beam. .......... 33
3.3 Three AIRs with different capabilities, each associated with a different set of targets, are used to grit-blast a flat plate. ................................. 34
3.4 Examples of unacceptable solutions where in each example at least one requirement is not met. ......................................................... 35
3.5 Two examples of Voronoi partitioning where the overlapped areas of two AIRs are partitioned based on the locations of the seed points. .......... 39
3.6 Three AIRs with different capabilities to operate on a flat surface. ................ 48
3.7 Pareto front from one of the optimization runs. ........................................ 48
3.8 Boxplots of the two objectives for the 10 optimization runs. ....................... 49
3.9 The test environment used in the pattern-based GA approach, HOGA approach, and the proposed APA approach is shown, and the paths generated using the APA approach are shown for two scenarios where in each scenario different initial start points are considered for the robots. ............................ 51
3.10 Two AIRs operating on a flat plate. ......................................................... 52
3.11 Results from two simulations. ................................................................. 53
3.12 Torque heatmaps of the two simulations. .................................................. 53
3.13 Overlapped and specific areas of two AIRs which will be used to spray paint three objects. ............................................................. 54
3.14 AIRs’ final paths created on the three objects based on three solutions chosen from the Pareto front. ................................................. 56
3.15 Trade-off for all combinations of the objectives. ....................................... 57
3.16 Boxplots of Objectives 2 to 4 for the 10 optimization runs. ....................... 58
3.17 Average of distances of individuals at each generation. ............................. 58
3.18 Three AIRs are used to operate on three different objects which are separated from each other. ......................................................... 59
List of Figures

3.19 Two solutions are shown where one of the solutions is not acceptable since missing sections are present, and the other solution is acceptable since all missing sections are found and allocated appropriately. 60
3.20 Reachable and overlapped areas of four AIRs with different capabilities. 62
3.21 Missing sections of four AIRs are fixed through further allocation. 63
3.22 Overlapped and specific areas as well as the final solution associated with the two AIRs which will be used as a test for a grit-blasting application in a steel bridge environment. 64
3.23 Overlapped and specific areas as well as the final solution associated with the two AIRs which will be used to grit-blast a concave boxlike steel structure. 66

4.1 The bases of two AIRs that are to grit-blast an I-beam are positioned appropriately relative to the I-beam and each other so as to jointly achieve complete coverage. 71
4.2 Two AIRs to cover all internal and external surfaces of a boxlike structure. 71
4.3 Discrete candidate base placements of two AIRs with different capacity, and the FBPs of the first AIR. 73
4.4 Two AIRs deployed to cover all surfaces of an I-beam. 75
4.5 A multi-part chromosome representation developed for the problem under consideration. 85
4.6 Multi-part chromosome representation with additional zero genes to deal with the uncertainty in determining the number of base placements to be visited by the AIRs. 86
4.7 An example of the crossover operation for the developed multi-part chromosome representation. 87
4.8 An example of the mutation operation where small positive or negative random integers are added to a small number of genes. 89
4.9 Three AIRs select base placements to grit-blast three objects. 95
4.10 The mock environment and its simulation, the location of the discrete base placements as well as the FBPs, and the result of the simulation. 96
4.11 Results for Objective 1 (percentage of missed coverage) and Objective 2 (makespan in seconds) of the 10 optimization runs. 98
4.12 Boxplots of Objectives 1 to 4 for the 10 optimization runs. 99
4.13 Pareto fronts for the first two optimization runs with respect to Objectives 1 and 2 only. 99
4.14 (a) Average of distances of individuals at each generation; and (b) average of distances of all individuals in each generation to the selected solution. 100
4.15 The vehicle, the point cloud representation and the target representation. 101
4.16 Paths generated on all reachable surfaces of the vehicle, where the paths shown as solid blue lines and dashed red lines are associated with AIRs 1 and 2, respectively. 102
4.17 The coverage of the path associated with the first AIR at its second base placement is checked using a laser that is installed at the end-effector of the AIR. 103
4.18 Boxplots of Objectives 1 to 4 for the 10 optimization runs. 104
4.19 Pareto front with respect to Objectives 1 and 2 only. 105
List of Figures

5.1 Two AIRs spray painting a large object. ........................................ 108
5.2 Discrete base placements of two AIRs with different capacity, and target representation of the surfaces. ........................................ 110
5.3 An experiment using a vehicle where two AIRs are deployed to grit-blast the surfaces of a vehicle. ........................................ 118
5.4 A simulation where three AIRs are operating on a complex object. ....... 120
6.1 A path by a prey due to grazing while avoiding a predator. ............... 126
6.2 The prey not covering certain regions due to close proximity to the predator. 134
6.3 Paths generated on the surface using different weighting factors or a different location for the predator. ........................................ 140
6.4 Eight different scenarios, and a path created for each scenario in real-time. 142
6.5 A scenario where two dynamic obstacles continuously move within the highlighted rectangular regions, and an example path where the robot covers the whole surface. ........................................ 145
6.6 An AIR is used to high-pressure clean a vehicle. ............................ 147
6.7 The areas expected to be covered by the AIR are shown. Optimization is performed to obtain appropriate weighting factors ($\omega^s = 0.45$ and $\omega^b = 0.96$) based on which the shown path is generated. ................. 148
6.8 The areas that can actually be covered by the AIR at its current base placement are shown, then the same weighting factors ($\omega^s = 0.45$ and $\omega^b = 0.96$) are used to generate the shown path. ................................. 148
6.9 The trajectory of each obstacle is shown, and an example path is provided. 150
6.10 An example path corresponding to scenario 1 of Table 6.5. ............... 152
6.11 A scenario where an obstacle continuously moves through the area that needs to be covered with a varying speed. ................................. 153

A.1 The AIR used in the case studies, its properties and sphere representation. 162

C.1 The workspace of an AIR is approximated as a sphere and is represented as many cube-shaped and equally-sized grids. Each grid is associated with many groups where each group contains many AIR poses that can reach the grid within a predefined angle relative to a surface normal. ................................. 169
List of Tables

3.1 Parameters related to the three AIRs. ........................................ 48
3.2 Three solutions from the Pareto front. ...................................... 55
3.3 Completion time of the AIRs in seconds. ................................. 57
3.4 Makespan value and computation time of the case studies. .......... 68
4.1 Three solutions from the Pareto front. ...................................... 97
5.1 Multi-objective hybrid GA-SA vs. NSGA-II. .............................. 119
5.2 Testing for different values of $\Sigma = I_2\sigma^2$ (for the scenario where 2 AIRs are grit-blasting a vehicle). ..................... 120
5.3 Testing for different values of $\Sigma = I_2\sigma^2$ (for the scenario where 3 AIRs are grit-blasting a complex object). ..................... 121
6.1 Result and comparison for each scenario: path lengths (m). ........ 143
6.2 Result and comparison for each scenario: difference in lengths (m / %). 143
6.3 Comparison against other adaptive approaches. .......................... 144
6.4 Results for 9 scenarios where in each scenario a single dynamic obstacle blocks the path of the AIR’s end-effector. .............. 149
6.5 Results for 4 scenarios where in each scenario multiple obstacles with different speeds and sizes block the path of an AIR’s end-effector. 151
6.6 Speed and size of each obstacle. .................................................. 152
A.1 Specification of the AIR’s actuators. ....................................... 163
C.1 Main properties of the lookup table used in the case studies. ....... 169
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIMM</td>
<td>Autonomous Industrial Mobile Manipulator</td>
</tr>
<tr>
<td>AIR</td>
<td>Autonomous Industrial Robot</td>
</tr>
<tr>
<td>APA</td>
<td>Area Partitioning and Allocation</td>
</tr>
<tr>
<td>AUV</td>
<td>Autonomous Underwater Vehicle</td>
</tr>
<tr>
<td>CAS</td>
<td>Centre for Autonomous Systems</td>
</tr>
<tr>
<td>CPP</td>
<td>Coverage Path Planning</td>
</tr>
<tr>
<td>DOF</td>
<td>Degrees Of Freedom</td>
</tr>
<tr>
<td>FBP</td>
<td>Favored Base Placement</td>
</tr>
<tr>
<td>GA</td>
<td>Genetic Algorithm</td>
</tr>
<tr>
<td>MOEA</td>
<td>Multi-Objective Evolutionary Algorithm</td>
</tr>
<tr>
<td>NSGA</td>
<td>Nondominated Sorting Genetic Algorithm</td>
</tr>
<tr>
<td>OMBP</td>
<td>Optimization of Multiple Base Placements for each AIR</td>
</tr>
<tr>
<td>POS</td>
<td>Pareto Optimal Solutions</td>
</tr>
<tr>
<td>PPCPP</td>
<td>Prey-Predator Coverage Path Planning</td>
</tr>
<tr>
<td>RFP</td>
<td>Robotic Fiber Placement</td>
</tr>
<tr>
<td>SA</td>
<td>Simulated Annealing</td>
</tr>
<tr>
<td>SD</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>UAV</td>
<td>Unmanned Aerial Vehicle</td>
</tr>
<tr>
<td>UTS</td>
<td>University of Technology Sydney</td>
</tr>
</tbody>
</table>
Nomenclature

General Referencing

\( x \)  A scalar
\( x^\text{ave} \)  A vector
\( X \)  A set
\( X \)  A matrix
\( x^{\prime\prime} \)  Front superscript is part of the notation and is used to help describe the parameter
\( x_{\ldots} \)  Front subscripts are indices unless mentioned otherwise

General Formatting Style

\( F(\ldots) \)  A scalar valued function
\( \mathbf{F}(\ldots) \)  A vector valued function
\( E[\ldots] \)  Expected valued function
\( [\ldots]^\top \)  Transpose
\{\ldots\}  A set
\(|\cdot|\)  Absolute value
\(\|\cdot\|\)  Vector length
\( (\cdot)^n \)  A parameter to the power of \( n \)
\( \mathcal{U}(\ldots) \)  Uniform Distribution
\( \mathcal{N}(\ldots) \)  Normal Distribution
Nomenclature

Specific Symbol Usage (Roman Symbols)

$A$ The surface areas representing the overlapped areas of the AIRs

$A_i$ The surface areas from the overlapped areas allocated to the $i$th AIR

$a_{ij}$ A surface area represented by the $j$th target, associated with the $i$th AIR

$B_i$ A set of discrete base placements for the $i$th AIR

$B_i^{FBP}$ A subset of base placements from the set $B_i$, which are called Favored Base Placements (FPBs)

$b_{ij}$ The $j$th discrete base placement from the set $B_i$

$C^v$ A set containing the Voronoi cells of all AIRs

$c_i^s$ The centroid of the $i$th AIR’s specific areas, i.e. areas that can only be covered by the $i$th AIR

$c_i^c$ A Voronoi cell representing part of the overlapped areas to be covered by the $i$th AIR

$D(o_j)$ A function that calculates the distance from the neighbor $o_j$ to the predator

$D_{\text{max}}(o_k)$ A function that calculates the maximum distance of the distances from the neighbors of the current prey target to the predator

$D_{\text{min}}(o_k)$ A function that calculates the minimum distance of the distances from the neighbors of the current prey target to the predator

$d_i$ The distance between two adjacent targets along a path of the $i$th AIR

$e_i$ The maximum anticipated errors in the base placement of the $i$th AIR

$F(P_i)$ A function that returns the fitness values for the $i$th GA population $P_i$

$F_j(Z)$ The $j$th objective function which is calculated based on the design variables in $Z$

$F^H$ The forces and moments generated at the frame $H$

$g_{ik}$ The $k$th nonzero gene in the $i$th part of a chromosome

$i, j, k, l, m$ Used as indices

$I^s$ A set containing the indices of the progress times in $T^s$

$J(q^f_i)$ A function that returns the Jacobian of the pose $q^f_i$ of the $i$th AIR

$K^{\text{max}}$ The maximum number of observations from a probability distribution which represents uncertainties in a base placement
Nomenclature

\( L^c(P^Z) \) A function that calculates the length of a path \( P^Z \) generated based on the design variables \( Z \) and by considering the sequence of, and the distance between, the covered targets

\( L^o_i(Z) \) A function that calculates the length of a path generated on the overlapped areas of the \( i \)th AIR based on the design variables in \( Z \)

\( l^s_i \) The length of a path generated on the specific areas of the \( i \)th AIR

\( N^N(o_j) \) A function that calculates the number of neighbors of the \( j \)th neighbor of the prey

\( N^o_i(Z) \) A function that calculates the number of targets along the paths of the \( i \)th AIR that are created on the overlapped areas

\( N^I(Z_{ik}) \) A function that calculates the number of target that can be reached with feasible poses of the \( i \)th AIR at the \( k \)th base placement based on \( Z_{ik} \)

\( N(o_k) \) A set of neighbors of the prey \( o_k \)

\( N^u(o_k) \) A set of uncovered and obstacle-free neighbors of the prey \( o_k \)

\( N^u(o_j) \) A set of uncovered neighbors of the \( j \)th neighbor \( o_j \) of the prey \( o_k \)

\( n \) The number of AIRs deployed

\( n^b_i \) The number of discrete base placements in the set \( B_i \)

\( n^c \) The number of loops where temperature is kept constant for the simulated annealing algorithm

\( n^D_i \) The number of nonzero genes selected from dad’s chromosome for the \( i \)th part of a chromosome

\( n^F_i \) The number of favored base placements (i.e. size of the set \( B_i^{FBP} \))

\( n^g_i \) The number of genes in the \( i \)th part of a chromosome (i.e. the length) corresponding to the \( i \)th AIR

\( n^{gen} \) The number of generations for the Genetic Algorithm

\( n^J_i \) The number of joints of the \( i \)th AIR

\( n^K \) The maximum number of observations from the distribution that represents uncertainties in a base placement

\( n^k \) The number of steps associated with a prey’s path

\( n^M_i \) The number of nonzero genes selected from mom’s chromosome for the \( i \)th part of a chromosome
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_k^N$</td>
<td>The number of neighbors of the prey at step $k$</td>
</tr>
<tr>
<td>$n_{N_{\text{max}}}$</td>
<td>The maximum possible number of neighbors of the prey target</td>
</tr>
<tr>
<td>$n^O$</td>
<td>The number of targets that represent the surface (if subscript $i$ is added then the targets are associated with the $i$th AIR)</td>
</tr>
<tr>
<td>$n^{O_{\text{r}}}$</td>
<td>The number of targets that represent the reachable areas (if subscript $i$ is added then the targets are associated with the $i$th AIR)</td>
</tr>
<tr>
<td>$n_i^O$</td>
<td>The number of targets in the overlapped areas, which are associated with the $i$th AIR</td>
</tr>
<tr>
<td>$n^P$</td>
<td>The population size for the Genetic Algorithm</td>
</tr>
<tr>
<td>$n_i^{\text{rej}}$</td>
<td>The number of rejected targets of the $i$th AIR, i.e. the targets in the overlapped areas that are not allocated to the $i$th AIR</td>
</tr>
<tr>
<td>$n_i^s$</td>
<td>The number of targets in the specific areas of the $i$th AIR</td>
</tr>
<tr>
<td>$n_i^T$</td>
<td>The number of targets associated with the $i$th AIR which represent all surfaces irrespective of whether or not the targets can be reached</td>
</tr>
<tr>
<td>$n^v$</td>
<td>The number of base placements to be visited by all AIRs</td>
</tr>
<tr>
<td>$n_i^v$</td>
<td>The number of base placements to be visited by the $i$th AIR</td>
</tr>
<tr>
<td>$O$</td>
<td>A set with a collection of sets where each set contains an AIR’s targets which represent all surfaces</td>
</tr>
<tr>
<td>$O_i$</td>
<td>A set of targets that are associated with the $i$th AIR and are used to represent all surfaces</td>
</tr>
<tr>
<td>$O_{dk}$</td>
<td>A set of targets that represent a surface and are within the workspace boundary of the $i$th AIR at the $k$th base placement</td>
</tr>
<tr>
<td>$O^{al}$</td>
<td>A set with a collection of sets where each set contains the allocated targets of the $i$th AIR</td>
</tr>
<tr>
<td>$O_i^{al}$</td>
<td>A set containing the targets that are allocated to the $i$th AIR</td>
</tr>
<tr>
<td>$O_i^c$</td>
<td>A set of targets that have already been covered by the $i$th AIR</td>
</tr>
<tr>
<td>$O_k^c$</td>
<td>A set of targets that have already been covered by the prey up-to step $k$</td>
</tr>
<tr>
<td>$O^o$</td>
<td>A set with a collection of sets where each set contains the overlapped targets of an AIR</td>
</tr>
<tr>
<td>$O_i^o$</td>
<td>A set of targets that represent the overlapped areas of the $i$th AIR, which more than one AIR can cover</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>$O_k^{ob}$</td>
<td>A set which contains all the targets that are predicted to be occupied by obstacles at step $k$</td>
</tr>
<tr>
<td>$O^r$</td>
<td>A set of targets that are reachable by an AIR with acceptable end-effector pose (if subscript $i$ is added then targets are associated with the $i$th AIR)</td>
</tr>
<tr>
<td>$O_{ik}^r$</td>
<td>A set of targets that represent a surface and are reachable from the $k$th base placement of the $i$th AIR</td>
</tr>
<tr>
<td>$O^{rej}$</td>
<td>A set with a collection of sets where each set contains the rejected targets of the $i$th AIR</td>
</tr>
<tr>
<td>$O_{i}^{rej}$</td>
<td>A set of targets in the overlapped areas that are not allocated (rejected) to the $i$th AIR</td>
</tr>
<tr>
<td>$O^s$</td>
<td>A set with a collection of sets where each set contains the targets of an AIR that represent the specific areas</td>
</tr>
<tr>
<td>$O_{i}^s$</td>
<td>A set of targets that represent the specific areas of the $i$th AIR, which only the $i$th AIR can cover</td>
</tr>
<tr>
<td>$O_{i}^u$</td>
<td>A set of targets that are assigned to the $i$th AIR but have not been covered (uncovered)</td>
</tr>
<tr>
<td>$O_k^u$</td>
<td>A set of targets that are not yet covered (uncovered) by the prey at step $k$</td>
</tr>
<tr>
<td>$o$</td>
<td>A target representing part of a surface</td>
</tr>
<tr>
<td>$o_k$</td>
<td>The prey target at step $k$ (the prey is defined as the coverage spot of the end-effector tool)</td>
</tr>
<tr>
<td>$o_{ij}$</td>
<td>The $j$th target associated with the $i$th AIR</td>
</tr>
<tr>
<td>$o_{ijk}$</td>
<td>The $k$th target that is within the workspace boundary of the $i$th AIR, and that might be reachable, at the $j$th base placement</td>
</tr>
<tr>
<td>$o_i$</td>
<td>The $i$th neighbor of the prey $o_k$ (from the set $N(o_k)$)</td>
</tr>
<tr>
<td>$o_j$</td>
<td>The $j$th uncovered and obstacle-free neighbor of the prey $o_k$ (from the set $N^u(o_k)$)</td>
</tr>
<tr>
<td>$o_{j_k}$</td>
<td>The neighbor of the prey with maximal reward at step $k$</td>
</tr>
<tr>
<td>$o_p^k$</td>
<td>The preceding target that was covered by the prey at $(k - 1)$th step</td>
</tr>
<tr>
<td>$o^s$</td>
<td>The start target of the prey</td>
</tr>
<tr>
<td>$P_i$</td>
<td>The $i$th population for the Genetic Algorithm</td>
</tr>
<tr>
<td>$P^Z$</td>
<td>A path generated based on the values of the design variables $Z$</td>
</tr>
</tbody>
</table>
Nomenclature

\( \mathcal{P} \)  
A chromosome (offspring) within a GA population

\( p_i^s \)  
The seed point of a Voronoi cell, which is associated with the \( i \)th AIR

\( q_i \)  
A pose of the \( i \)th AIR, which is defined by the joints angles of the AIR

\( q_{ij}^f \)  
A feasible pose of the \( i \)th AIR that reaches the \( j \)th target with correct end-effector position and orientation, and without collision

\( R(o_j) \)  
The total reward function associated with the target \( o_j \)

\( R^s(o_j) \)  
The smoothness reward function associated with the target \( o_j \)

\( R^b(o_j) \)  
The boundary reward function associated with the target \( o_j \)

\( R^d(o_j) \)  
The distance reward function associated with the target \( o_j \)

\( r \)  
The radius of a sphere within which targets are considered to be neighbors of a target/prey

\( r^o \)  
The radius of a target

\( r_{ij}^o \)  
The radius of the \( j \)th target of the \( i \)th AIR

\( T_i(Z) \)  
A function that calculates the overall completion time of the \( i \)th AIR based on the design variables in \( Z \)

\( T_{ik}(q_{ij}^f) \)  
A function that calculates the torque experienced by the \( k \)th joint of the \( i \)th AIR at pose \( q_{ij}^f \)

\( T^q(q_{ij}^f) \)  
A function that calculates the torque values of all joints due to the forces at a frame and the AIR pose \( q_{ij}^f \)

\( T^{R_{\text{max}}}(q_{ij}^f) \)  
A function that calculates the maximum torque ratio due to one of the \( i \)th AIR’s joints and the AIR pose \( q_{ij}^f \)

\( T^a_{\text{al}} \)  
A set containing the maximum torque ratios corresponding to the allocated targets of the \( i \)th AIR

\( T^r_{\text{rej}} \)  
A set containing the maximum torque ratios corresponding to the rejected targets of the \( i \)th AIR

\( T^s \)  
A set containing the progress times of the \( n \) AIRs sorted from the lowest time to the highest

\( t \)  
The current execution time of the coverage task

\( \bar{t} \)  
The average of the completion times of the \( n \) AIRs

\( t_i \)  
The current progress time of the \( i \)th AIR

\( t^c \)  
The overall completion time of the task (makespan)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_i )</td>
<td>The time associated with the ( i )th AIR setting-up and moving to the next base placement</td>
</tr>
<tr>
<td>( t_{\text{max}} )</td>
<td>The maximum time allocated to the coverage task</td>
</tr>
<tr>
<td>( v_i )</td>
<td>The end-effector speed of the ( i )th AIR</td>
</tr>
<tr>
<td>( v^d_i )</td>
<td>The difference between the maximum and the minimum end-effector speed of the ( i )th AIR</td>
</tr>
<tr>
<td>( v_{i}^{\text{max}} )</td>
<td>The maximum end-effector speed of the ( i )th AIR</td>
</tr>
<tr>
<td>( v_{i}^{\text{min}} )</td>
<td>The minimum end-effector speed of the ( i )th AIR</td>
</tr>
<tr>
<td>( W(q_i^f) )</td>
<td>A function that calculates the manipulability measure of the pose ( q_i^f )</td>
</tr>
<tr>
<td>( W_{i}^{al} )</td>
<td>A set containing the manipulability measure associated with the allocated targets of the ( i )th AIR</td>
</tr>
<tr>
<td>( W_{i}^{rej} )</td>
<td>A set containing the manipulability measure associated with the rejected targets of the ( i )th AIR</td>
</tr>
<tr>
<td>( Y^p )</td>
<td>The output of the multi-objective optimization which is a set of solutions on the Pareto front</td>
</tr>
<tr>
<td>( y^f )</td>
<td>The final solution chosen from the Pareto front (i.e. from ( Y^p ))</td>
</tr>
<tr>
<td>( Z )</td>
<td>A set containing the design variables</td>
</tr>
<tr>
<td>( Z_{ik} )</td>
<td>The ( k )th design variable associated with the ( i )th AIR</td>
</tr>
</tbody>
</table>

**Specific Symbol Usage (Greek Symbols)**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_i )</td>
<td>The cooling ratio for the simulated annealing algorithm, corresponding to the ( i )th objective function</td>
</tr>
<tr>
<td>( \beta_i )</td>
<td>A favored base placement from the set ( B_i^{FBP} ), associated with the ( i )th AIR</td>
</tr>
<tr>
<td>( \beta_{i}^{AIR}(t) )</td>
<td>The base placement of the ( i )th AIR at time ( t )</td>
</tr>
<tr>
<td>( \delta )</td>
<td>The minimum distance threshold between the base placements of any two AIRs</td>
</tr>
<tr>
<td>( \delta_{ik}^s )</td>
<td>A small negative or positive integer to be added to the gene ( g_{ik} )</td>
</tr>
<tr>
<td>( \theta_j )</td>
<td>The angle of the ( j )th joint of an AIR pose</td>
</tr>
<tr>
<td>( \Xi^z )</td>
<td>A set with each element in the set representing the uncertainties associated with an AIR’s base placements expressed as a random vector with multivariate normal distribution</td>
</tr>
</tbody>
</table>
Nomenclature

\[ \xi_{ij} \]
An observation from a probability distribution which represents uncertainties in the \( j \)th base placement of the \( i \)th AIR

\[ \xi^k \]
The \( k \)th observation from a probability distribution which represents uncertainties in a base placement

\[ \Sigma \]
The covariance matrix associated with a multivariate normal distribution

\[ \sigma^2 \]
The variance

\[ \tau_i \]
The initial temperature for the simulated annealing algorithm, corresponding to the \( i \)th objective function

\[ \tau_{ik}^c \]
The torque capacity of the \( k \)th joint of the \( i \)th AIR

\[ \psi \]
The predator location

\[ \omega_{ikj} \]
A weighting factor (from 0 to 1) applied to the end-effector speed of the \( i \)th AIR based on the area in which the target \( o_{ikj} \) is located

\[ \omega^s \]
A weighting factor for the smoothness reward function

\[ \omega^b \]
A weighting factor for the boundary reward function
## Glossary of Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR path</td>
<td>The path that an AIR follows by adjusting its joints angles and base position/orientation.</td>
</tr>
<tr>
<td>AIR pose</td>
<td>A pose of an AIR defined by its joints angles and base position/orientation.</td>
</tr>
<tr>
<td>AIR team’s objectives</td>
<td>A set of objectives, formulated as objective functions, that the AIR team aim to optimize. Examples include achieving minimal completion time and maximal coverage.</td>
</tr>
<tr>
<td>Allocated areas</td>
<td>Part of the surface areas of interest allocated to an AIR for coverage.</td>
</tr>
<tr>
<td>Autonomous Industrial Robot (AIR)</td>
<td>An industrial robot, with or without a mobile platform, that has the intelligence needed to operate autonomously in a complex and unstructured environment. This intelligence includes self-awareness, environmental awareness and collision avoidance.</td>
</tr>
<tr>
<td>Base placement</td>
<td>A base location and orientation for an AIR from which it will operate on a surface or part of a surface.</td>
</tr>
<tr>
<td>Boundary reward</td>
<td>The reward associated with the prey covering the targets representing the boundary (boundary targets).</td>
</tr>
<tr>
<td>Boundary targets</td>
<td>The targets that represent the boundary of the surface as well as the targets that are on the boundary of the uncovered regions, i.e. the uncovered targets closest to the already covered region of the surface.</td>
</tr>
<tr>
<td>Complete coverage</td>
<td>The task of covering (operating on) all areas of a surface.</td>
</tr>
</tbody>
</table>
Complete coverage path A path on a surface of interest that when covered (followed from start to end) by an end-effector tool of an AIR it will result in complete coverage of the surface.

Complex object A 3D object with complex geometric shape.

Coverage area The area to be covered (operated on) by the AIRs’ end-effector tool, and excludes the area occupied by obstacles.

Covered targets The targets on the surface that have been covered (operated on) by one or more AIRs.

Deadlock The situation where the prey arrives at a target where all neighbors are already covered. In this case, the prey needs to repeat coverage of a certain number of targets in order to reach an uncovered target. PPCPP resumes when the prey reaches an uncovered target.

Dynamic environment An environment where changes can occur, e.g. stationary or dynamic obstacles may become present. Changes in the environment can be unexpected, i.e. prior to real-time implementation it may not be possible to predict the changes.

End-effector A point, an area, or a tool at the end of an AIR’s arm that interacts with the environment, e.g. the blasting spot in the grit-blasting application or the spray spot in the spray painting application.

End-effector pose The position and orientation of the end-effector relative to a reference frame.

Environment A space consisting of AIRs, objects to operate on which can be complex or planar, and dynamic or stationary obstacles.

Exploration The process in which AIRs navigate and explore an unknown (or partially unknown) environment to obtain information about it and build a map.

Favored Base Placement (FBP) A base placements for an AIR that results in reasonably high coverage of a surface and that is an acceptable distance away from obstacles.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feasible AIR pose</td>
<td>An AIR pose that can reach a target with appropriate end-effector orientation and position, and without any collision.</td>
</tr>
<tr>
<td>Localization</td>
<td>The process of determining the location and/or orientation of an AIR with respect to a reference point or frame.</td>
</tr>
<tr>
<td>Makespan</td>
<td>The overall completion time of a task.</td>
</tr>
<tr>
<td>Manipulator</td>
<td>In this thesis, a manipulator is an industrial robotic arm which forms part of an AIR.</td>
</tr>
<tr>
<td>Manipulability measure</td>
<td>A measure for a manipulator pose which indicates how far the manipulator is from singularities.</td>
</tr>
<tr>
<td>Mapping</td>
<td>The process of constructing a map of the environment (including the objects) in which the AIR operates.</td>
</tr>
<tr>
<td>Missed-coverage</td>
<td>The condition where part of a surface is not covered by any AIR.</td>
</tr>
<tr>
<td>Missing sections</td>
<td>The sections of the surface that are missed due to a special condition where more than two AIRs are deployed.</td>
</tr>
<tr>
<td>Neighbor</td>
<td>A neighboring target of the prey (or another target) which belongs to the neighboring set.</td>
</tr>
<tr>
<td>Obstacle</td>
<td>A stationary or a dynamic object that an AIR can collide with due to the object being inside the AIR’s workspace for a period of time.</td>
</tr>
<tr>
<td>Overlapped areas</td>
<td>The surface areas that more than one AIR can reach with feasible AIR poses as a result of AIRs’ workspace overlapping.</td>
</tr>
<tr>
<td>Pareto front</td>
<td>A set of Pareto optimal solutions, which is the output of a multi-objective optimization algorithm. All Pareto optimal solutions are considered to be equal in terms of optimality.</td>
</tr>
<tr>
<td>Planar environment</td>
<td>An environment where the surface or the object to be operated on can be approximated to be flat.</td>
</tr>
<tr>
<td>Platform</td>
<td>A mobile or stationary platform on which the AIR’s manipulator is fixed.</td>
</tr>
<tr>
<td>Prey</td>
<td>The prey is the coverage spot with a size equivalent to the coverage size of an AIR’s end-effector tool.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Predation avoidance reward</td>
<td>The reward associated with the prey maximizing its distance from the predator at each step.</td>
</tr>
<tr>
<td>Predator</td>
<td>A point represented as a virtual predator that a prey considers avoiding by maximizing its distance from it.</td>
</tr>
<tr>
<td>Reachable target</td>
<td>A target that can be reached by a feasible AIR pose.</td>
</tr>
<tr>
<td>Smoothness reward</td>
<td>The reward associated with the prey continuing motion in a straight direction.</td>
</tr>
<tr>
<td>Specific areas</td>
<td>The surface areas that can be reached, with feasible AIR poses, by one of the AIRs only.</td>
</tr>
<tr>
<td>Surface normal</td>
<td>A 3D vector perpendicular to the surface.</td>
</tr>
<tr>
<td>Target</td>
<td>A circular disk that represents part of a surface; and is defined using the location of the disk’s centroid, the surface normal, and the radius of the disk.</td>
</tr>
<tr>
<td>Target normal</td>
<td>A 3D vector perpendicular to the target.</td>
</tr>
<tr>
<td>Task execution</td>
<td>The process of executing the planned task (e.g. grit-blasting or spray painting) by the AIRs after all necessary off-line computations or preparations are completed.</td>
</tr>
<tr>
<td>Total reward</td>
<td>The total reward associated with the prey moving to one of the neighbors.</td>
</tr>
<tr>
<td>Uncovered targets</td>
<td>The targets that are not covered by any AIR.</td>
</tr>
<tr>
<td>Unexpected obstacles</td>
<td>The stationary or dynamic obstacles that are initially unknown to the AIR and are detected in real-time during the coverage task.</td>
</tr>
<tr>
<td>Unstructured environment</td>
<td>A complex and uncontrolled real-world environment which is similar to human-like environments and is subject to regular changes and inherent uncertainties.</td>
</tr>
<tr>
<td>Voronoi cell</td>
<td>A cell that represents part of a surface and is allocated to an AIR. The cell is created using Voronoi partitioning method where an area is divided into n cells based on the location of n seed points.</td>
</tr>
</tbody>
</table>