UNIVERSITY OF TECHNOLOGY SYDNEY

Enabling Methodologies for Optimal Coverage by Multiple Autonomous Industrial Robots

by

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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.

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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.

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Abbreviations

AIMM	**A**utonomous **I**ndustrial **M**obile **M**anipulator
AIR	**A**utonomous **I**ndustrial **R**obot
APA	**A**rea **P**artitioning and **A**llocation
AUV	**A**utonomous **U**nderwater **V**ehicle
CAS	**C**entre for **A**utonomous **S**ystems
CPP	**C**overage **P**ath **P**lanning
DOF	**D**egrees **O**f **F**reedom
FBP	**F**avored **B**ase **P**lacement
GA	**G**enetic **A**lgorithm
MOEA	**M**ulti-**O**bjective **E**volutionary **A**lgorithm
NSGA	**N**ondominated **S**orting **G**enetic **A**lgorithm
OMBP	**O**ptimization of **M**ultiple **B**ase **P**lacements for each AIR
POS	**P**areto **O**ptimal **S**olutions
PPCPP	**P**rey-**P**redator **C**overage **P**ath **P**lanning
RFP	**R**obotic **F**iber **P**lacement
SA	**S**imulated **A**nnealing
SD	**S**tandard **D**eviation
UAV	**U**nmanned **A**erial **V**ehicle
UTS	**U**niversity of **T**echnology **S**ydney

Nomenclature

General Referencing

x	A scalar
$\boldsymbol{x}$	A vector
X	A set
$\boldsymbol{X}$	A matrix
$x^{\cdots}$	Front superscript is part of the notation and is used to help describe the parameter
$x_{\cdots}$	Front subscripts are indices unless mentioned otherwise

General Formatting Style

$\mathrm{F}(\cdots)$	A scalar valued function
$\mathbf{F}(\cdots)$	A vector valued function
$E[\cdots]$	Expected valued function
$[\cdots]^{\mathsf{T}}$	Transpose
$\{\cdots\}$	A set
$\lvert\cdot\rvert$	Absolute value
$\lVert\cdot\rVert$	Vector length
$(\,\cdot\,)^n$	A parameter to the power of n
$\mathcal{U}(\cdots)$	Uniform Distribution
$\mathcal{N}(\cdots)$	Normal Distribution

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 ith AIR
a_{ij}^t	A surface *area* represented by the jth *target*, associated with the ith AIR
B_i	A set of discrete *base* placements for the ith AIR
B_i^{FBP}	A subset of *base* placements from the set B_i, which are called Favored Base Placements ($FPBs$)
$\boldsymbol{b}_{ij}$	The jth discrete *base* placement from the set B_i
C^v	A set containing the *Voronoi cells* of all AIRs
$\boldsymbol{c}_i^s$	The *centroid* of the ith AIR's *specific* areas, i.e. areas that can only be covered by the ith AIR
c_i^v	A *Voronoi cell* representing part of the overlapped areas to be covered by the ith AIR
$\mathrm{D}(\boldsymbol{o}_j)$	A function that calculates the *distance* from the neighbor $\boldsymbol{o}_j$ to the predator
$\mathrm{D}^{max}(\boldsymbol{o}_k)$	A function that calculates the *maximum distance* of the distances from the neighbors of the current prey target to the predator
$\mathrm{D}^{min}(\boldsymbol{o}_k)$	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 ith AIR
e_i	The maximum anticipated *errors* in the base placement of the ith AIR
$\mathbf{F}(\boldsymbol{P}_i)$	A function that returns the *fitness* values for the ith GA population $\boldsymbol{P}_i$
$\mathrm{F}_j(Z)$	The jth objective *function* which is calculated based on the design variables in Z
$\boldsymbol{F}^H$	The *forces* and moments generated at the frame H
g_{ik}	The kth nonzero *gene* in the ith 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
$\mathbf{J}(q_i^f)$	A function that returns the *Jacobian* of the pose $\boldsymbol{q}_i^f$ of the ith AIR
K^{max}	The *maximum* number of observations from a probability distribution which represents uncertainties in a base placement

$\mathrm{L}^c(P^Z)$	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
$\mathrm{L}_i^o(Z)$	A function that calculates the *length* of a path generated on the *overlapped* areas of the ith AIR based on the design variables in Z
l_i^s	The *length* of a path generated on the *specific* areas of the ith AIR
$\mathrm{N}^N(\boldsymbol{o}_j)$	A function that calculates the *number* of *neighbors* of the jth neighbor of the prey
$\mathrm{N}_i^o(Z)$	A function that calculates the *number* of targets along the paths of the ith AIR that are created on the *overlapped* areas
$\mathrm{N}^f(Z_{ik})$	A function that calculates the *number* of target that can be reached with *feasible* poses of the ith AIR at the kth base placement based on Z_{ik}
$N(\boldsymbol{o}_k)$	A set of *neighbors* of the prey $\boldsymbol{o}_k$
$N^u(\boldsymbol{o}_k)$	A set of *uncovered* and *obstacle-free neighbors* of the prey $\boldsymbol{o}_k$
$N^u(\boldsymbol{o}_j)$	A set of *uncovered neighbors* of the jth neighbor $\boldsymbol{o}_j$ of the prey $\boldsymbol{o}_k$
n	The *number* of AIRs deployed
n_i^b	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_i^D	The *number* of nonzero genes selected from *dad*'s chromosome for the ith part of a chromosome
n_i^F	The *number* of *favored* base placements (i.e. size of the set B_i^{FBP})
n_i^g	The *number* of *genes* in the ith part of a chromosome (i.e. the length) corresponding to the ith AIR
n^{gen}	The *number* of *generations* for the Genetic Algorithm
n_i^J	The *number* of *joints* of the ith 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_i^M	The *number* of nonzero genes selected from *mom*'s chromosome for the ith part of a chromosome

n_k^N	The *number* of *neighbors* of the prey at step k
$n^{N_{max}}$	The *maximum* possible *number* of *neighbors* of the prey target
n^O	The *number* of *targets* that represent the surface (if subscript i is added then the targets are associated with the ith AIR)
n^{O^r}	The *number* of *targets* that represent the *reachable* areas (if subscript i is added then the targets are associated with the ith AIR)
n_i^o	The *number* of targets in the *overlapped* areas, which are associated with the ith AIR
n^p	The *population* size for the Genetic Algorithm
n_i^{rej}	The *number* of *rejected* targets of the ith AIR, i.e. the targets in the overlapped areas that are not allocated to the ith AIR
n_i^s	The *number* of targets in the *specific* areas of the ith AIR
n_i^T	The *number* of targets associated with the ith AIR which represent all surfaces irrespective of whether or not the targets can be reached
n^v	The *number* of base placements to be *visited* by all AIRs
n_i^v	The *number* of base placements to be *visited* by the ith AIR
O	A set with a collection of sets where each set contains an AIR's *targets* which represent all surfaces
O_i	A set of *targets* that are associated with the ith AIR and are used to represent all surfaces
O_{ik}	A set of *targets* that represent a surface and are within the workspace boundary of the ith AIR at the kth base placement
O^{al}	A set with a collection of sets where each set contains the *allocated targets* of the ith AIR
O_i^{al}	A set containing the *targets* that are *allocated* to the ith AIR
O_i^c	A set of *targets* that have already been *covered* by the ith AIR
O_k^c	A set of *targets* that have already been *covered* by the prey up-to step k
O^o	A set with a collection of sets where each set contains the *overlapped targets* of an AIR
O_i^o	A set of *targets* that represent the *overlapped* areas of the ith AIR, which more than one AIR can cover

O_k^{ob}	A set which contains all the targets that are predicted to be occupied by *obstacles* at step k
O^r	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 ith AIR)
O_{ik}^r	A set of *targets* that represent a surface and are *reachable* from the kth base placement of the ith AIR
O^{rej}	A set with a collection of sets where each set contains the *rejected targets* of the ith AIR
O_i^{rej}	A set of *targets* in the overlapped areas that are not allocated (*rejected*) to the ith AIR
O^s	A set with a collection of sets where each set contains the *targets* of an AIR that represent the *specific* areas
O_i^s	A set of *targets* that represent the *specific* areas of the ith AIR, which only the ith AIR can cover
O_i^u	A set of *targets* that are assigned to the ith AIR but have not been covered (*uncovered*)
O_k^u	A set of *targets* that are not yet covered (*uncovered*) by the prey at step k
$\boldsymbol{o}$	A *target* representing part of a surface
$\boldsymbol{o}_k$	The prey *target* at step k (the prey is defined as the coverage spot of the end-effector tool)
$\boldsymbol{o}_{ij}$	The jth *target* associated with the ith AIR
$\boldsymbol{o}_{ijk}$	The kth *target* that is within the workspace boundary of the ith AIR, and that might be reachable, at the jth base placement
$\boldsymbol{o}_i$	The ith *neighbor* of the prey $\boldsymbol{o}_k$ (from the set $N(\boldsymbol{o}_k)$)
$\boldsymbol{o}_j$	The jth uncovered and obstacle-free *neighbor* of the prey $\boldsymbol{o}_k$ (from the set $N^u(\boldsymbol{o}_k)$)
$\boldsymbol{o}_{j_k^*}$	The *neighbor* of the prey with maximal reward at step k
$\boldsymbol{o}_k^p$	The *preceding target* that was covered by the prey at $(k-1)$th step
$\boldsymbol{o}^s$	The *start target* of the prey
$\boldsymbol{P}_i$	The ith *population* for the Genetic Algorithm
P^Z	A *path* generated based on the values of the design variables Z

$\mathcal{P}$	A chromosome (offspring) within a GA population
$\boldsymbol{p}_i^s$	The *seed point* of a Voronoi cell, which is associated with the ith AIR
$\boldsymbol{q}_i$	A pose of the ith AIR, which is defined by the joints angles of the AIR
$\boldsymbol{q}_{ij}^f$	A *feasible* pose of the ith AIR that reaches the jth target with correct end-effector position and orientation, and without collision
$\mathrm{R}(\boldsymbol{o}_j)$	The total *reward* function associated with the target $\boldsymbol{o}_j$
$\mathrm{R}^s(\boldsymbol{o}_j)$	The *smoothness reward* function associated with the target $\boldsymbol{o}_j$
$\mathrm{R}^b(\boldsymbol{o}_j)$	The *boundary reward* function associated with the target $\boldsymbol{o}_j$
$\mathrm{R}^d(\boldsymbol{o}_j)$	The *distance reward* function associated with the target $\boldsymbol{o}_j$
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 jth *target* of the ith AIR
$\mathrm{T}_i(Z)$	A function that calculates the overall completion *time* of the ith AIR based on the design variables in Z
$\mathfrak{T}_{ik}(\boldsymbol{q}_i^f)$	A function that calculates the *torque* experienced by the kth joint of the ith AIR at pose $\boldsymbol{q}_i^f$
$\mathbf{T}^q(\boldsymbol{q}_{ij}^f)$	A function that calculates the *torque* values of all joints due to the forces at a frame and the AIR pose $\boldsymbol{q}_{ij}^f$
$\mathfrak{T}^{Rmax}(\boldsymbol{q}_i^f)$	A function that calculates the *maximum torque ratio* due to one of the ith AIR's joints and the AIR pose $\boldsymbol{q}_i^f$
$\mathcal{T}_i^{al}$	A set containing the maximum *torque* ratios corresponding to the *allocated* targets of the ith AIR
$\mathcal{T}_i^{rej}$	A set containing the maximum *torque* ratios corresponding to the *rejected* targets of the ith 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 ith AIR
t^c	The overall *completion time* of the task (makespan)

t_i^s	The *time* associated with the ith AIR *setting-up* and moving to the next base placement
t^{max}	The *maximum time* allocated to the coverage task
v_i	The end-effector speed of the ith AIR
v_i^d	The *difference* between the maximum and the minimum end-effector speed of the ith AIR
v_i^{max}	The *maximum* end-effector speed of the ith AIR
v_i^{min}	The *minimum* end-effector speed of the ith AIR
$\mathrm{W}(\boldsymbol{q}_i^f)$	A function that calculates the manipulability measure of the pose $\boldsymbol{q}_i^f$
W_i^{al}	A set containing the manipulability measure associated with the *allocated* targets of the ith AIR
W_i^{rej}	A set containing the manipulability measure associated with the *rejected* targets of the ith AIR
Y^p	The output of the multi-objective optimization which is a set of solutions on the *Pareto* front
$\boldsymbol{y}^f$	The *final* solution chosen from the Pareto front (i.e. from Y^p)
Z	A set containing the design variables
Z_{ik}	The kth design variable associated with the ith AIR

Specific Symbol Usage (Greek Symbols)

α_i	The cooling ratio for the simulated annealing algorithm, corresponding to the ith objective function
$\boldsymbol{\beta}_i$	A favored *base* placement from the set B_i^{FBP}, associated with the ith AIR
$\boldsymbol{\beta}_i^{AIR}(t)$	The *base* placement of the ith *AIR* at time t
δ	The minimum distance threshold between the base placements of any two AIRs
δ_{ik}^s	A *small* negative or positive integer to be added to the gene g_{ik}
θ_j	The *angle* of the jth joint of an AIR pose
Ξ^z	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

$\boldsymbol{\xi}_{ij}$	An observation from a probability distribution which represents uncertainties in the jth base placement of the ith AIR
$\boldsymbol{\xi}^k$	The kth observation from a probability distribution which represents uncertainties in a base placement
$\boldsymbol{\Sigma}$	The covariance matrix associated with a multivariate normal distribution
σ^2	The variance
τ_i	The initial *temperature* for the simulated annealing algorithm, corresponding to the ith objective function
τ_{ik}^c	The torque *capacity* of the kth joint of the ith AIR
$\boldsymbol{\psi}$	The predator location
ω_{ikj}	A weighting factor (from 0 to 1) applied to the end-effector speed of the ith AIR based on the area in which the target o_{ikj} is located
ω^s	A weighting factor for the *smoothness* reward function
ω^b	A weighting factor for the *boundary* reward function

Glossary of Terms

AIR path	The path that an AIR follows by adjusting its joints angles and base position/orientation.
AIR pose	A pose of an AIR defined by its joints angles and base position/orientation.
AIR team's objectives	A set of objectives, formulated as objective functions, that the AIR team aim to optimize. Examples include achieving minimal completion time and maximal coverage.
Allocated areas	Part of the surface areas of interest allocated to an AIR for coverage.
Autonomous Industrial Robot (AIR)	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.
Base placement	A base location and orientation for an AIR from which it will operate on a surface or part of a surface.
Boundary reward	The reward associated with the prey covering the targets representing the boundary (boundary targets).
Boundary targets	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.
Complete coverage	The task of covering (operating on) all areas of a surface.

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.

Feasible AIR pose	An AIR pose that can reach a target with appropriate end-effector orientation and position, and without any collision.
Localization	The process of determining the location and/or orientation of an AIR with respect to a reference point or frame.
Makespan	The overall completion time of a task.
Manipulator	In this thesis, a manipulator is an industrial robotic arm which forms part of an AIR.
Manipulability measure	A measure for a manipulator pose which indicates how far the manipulator is from singularities.
Mapping	The process of constructing a map of the environment (including the objects) in which the AIR operates.
Missed-coverage	The condition where part of a surface is not covered by any AIR.
Missing sections	The sections of the surface that are missed due to a special condition where more than two AIRs are deployed.
Neighbor	A neighboring target of the prey (or another target) which belongs to the neighboring set.
Obstacle	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.
Overlapped areas	The surface areas that more than one AIR can reach with feasible AIR poses as a result of AIRs' workspace overlapping.
Pareto front	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.
Planar environment	An environment where the surface or the object to be operated on can be approximated to be flat.
Platform	A mobile or stationary platform on which the AIR's manipulator is fixed.
Prey	The prey is the coverage spot with a size equivalent to the coverage size of an AIR's end-effector tool.

Predation avoidance reward	The reward associated with the prey maximizing its distance from the predator at each step.
Predator	A point represented as a virtual predator that a prey considers avoiding by maximizing its distance from it.
Reachable target	A target that can be reached by a feasible AIR pose.
Smoothness reward	The reward associated with the prey continuing motion in a straight direction.
Specific areas	The surface areas that can be reached, with feasible AIR poses, by one of the AIRs only.
Surface normal	A 3D vector perpendicular to the surface.
Target	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.
Target normal	A 3D vector perpendicular to the target.
Task execution	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.
Total reward	The total reward associated with the prey moving to one of the neighbors.
Uncovered targets	The targets that are not covered by any AIR.
Unexpected obstacles	The stationary or dynamic obstacles that are initially unknown to the AIR and are detected in real-time during the coverage task.
Unstructured environment	A complex and uncontrolled real-world environment which is similar to human-like environments and is subject to regular changes and inherent uncertainties.
Voronoi cell	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.