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Analysis of Existing Algorithms for the Coordination of Heterogeneous Robotic Teams

Bachelorarbeit Nummer der Arbeit

Institut für Regelungs- und Steuerungssysteme
Institutsleiter: Prof. Dr.-Ing. Sören Hohmann

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Hier sollte die Aufgabenstellung kurz beschrieben werden...maximal diese Seite, sodass unten noch Platz für die entsprechenden Angaben bleibt

(Prof. Dr.-Ing. Sören Hohmann)

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Jonas Teufel

Acknowledgments

I like to acknowledge ...

Abstract

Hier sollte eine kurze Zusammenfassung der Arbeit gegeben werden: Maximal eine halbe Seite!

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Abbreviations and Symbols

Abbreviations

Abbreviation	Meaning
ACO	Ant Colony Optimization
AVNS	Adaptive Variable Neighborhood Search
ALNS	Adaptive Large Neighborhood Search
BnB	Branch and Bound
BnP	Branch and Price
CP	Constrained Programming
GA	Genetic Algorithm
HHCP	Home Health Care Problem
IP	Integer Programming
MA	Memetic Algorithm
ME	MAP-Elites (Multi-dimensional Archive of Phenotypic Elites)
MIP	Mixed Integer Programming
MRTA	Multi Robot Task Allocation Problem
OP	Orienteering Problem
PCTSP	Price Collecting Traveling Salesperson Problem
PTP	Profitable Tour Problem
VNS	Variable Neighborhood Search
VRP	Vehicle Routing Problem
VRSP	Vehicle Routing and Scheduling Problem
VSP	Vehicle Scheduling Problem
SA	Simulated Annealing
TOP	Team Orienteering Problem
TS	Tabu Search
TSP	Traveling Salesman Problem
WSRP	Workforce Routing and Scheduling Problem

Latin letters

Symbol	Meaning
t	Zeit
u	Eingangsgröße
x	Zustandsgröße
y	Ausgangsgröße

Greek letters

Symbol	Meaning
π	Kreiszahl
$\sigma(t)$	Einheitssprung
τ	Zeitkonstante

Calligraphic and other symbols

Symbol	Meaning
$\mathcal{F}$	Transformation
$\mathbb{R}$	Menge der reellen Zahlen
$\Im$	Imaginärteil
$\Re$	Realteil

Indices, exponents and operator names

Symbol	Meaning
abs	absolut
eff	Effektivwert
ref	Referenz

Chapter 1

Introduction

1.1 Motivation

So for the motivation I should probably first of all read other motivation chapters from other people to get a feel for it. Also I guess here I would be mentioning the ARCHES project, but also all the other kinds of things that are possible with heterogeneous robot teams?

1.2 Aim

nothing

1.3 Contribution

nothing

1.4 Outline

nothing

Chapter 2

Literature Review

This chapter will present a literature review for both the *Multi-Robot Task Allocation Problem* (MRTA) as well as the *Vehicle Routing Problem* (VRP).
Section 2.1 will start of with providing a taxonomy for the MRTA, which will highlight relevant characteristics of different problem classes with varying degrees of difficulty. Section 2.2 will be an introduction to the area of routing problems in general, as well as the VRP and one of it's taxonomies specifically. This section will close with a comparison between the presented taxonomies for both MRTA and VRP. Following in section 2.4 will be a general overview of the relevant algorithmic architectures applied to solving the VRP. Section 2.5 will showcase various sub-areas of the broader vehicle routing field, which have turned out to display especially relevant similarities to the specific problem characteristics shown in [AIM?]. The chapter will end with a presentation of specific selected approaches found in the VRP literature in section 2.6. These approaches will be evaluated and the most promising will be chosen for further investigation in the following chapters of the thesis.

2.1 Taxonomy of Multi-Robot Coordination Problems

The human strive for knowledge produces an ever increasing body of research of all kinds. With close to 8 billion humans currently alive, the output of research articles, data sets, books etc. has also reached new dimensions. A newly established domain of research can grow from just a handful of publications to virtually filling entire bookshelves in the span of a few years. It has become near impossible for a single human to maintain a full overview of all the relevant developments even in their related sub field. For the purpose of gaining this sort of overview over complex problem domains, *taxonomies* are frequently introduced into the literature. They provide the means of structuring the subject of a specific problem field into various meaningful categories. These categories can help the human understanding of how aspects of a problem can be delimited, but also how they relate to one another. Like well structured filing cabinets can bring order to physical entities, taxonomies can help to bring mental order to abstracts concepts.

For the research field of multi-robot coordination, an initial taxonomy was provided by Gerkey and Matarić [GM]. In their publication the authors explain that prior to introducing a taxonomy much of the work within the field of multi-robot coordination was primarily "ad hoc and empirical". The motivation of introducing this taxonomy was provided by the desire to lay out the more theoretical foundations of the field relating to combinatorial optimization problems.
The taxonomy is formulated on an abstract level, leaving out implementation details for the robots. Robots are simply assumed to be agents, able to perform different activities with their concrete implementation being unimportant for a top-level coordination of those agents. The taxonomy is structured using three binary categories to describe underlying problem characteristics:

- **Single-Task Robots (ST) / Multi-Task Robots (MT)**
- **Single-Robot Tasks (SR) / Multi-Robot Tasks (MR)**
- **Instantaneous Assignment (IA) / Time-Extended Assignment (TA)**

Considering all possible classification combinations of problems results in a total of $2^3 = 8$ problem classes. Such a problem class would be identified by the combination of the abbreviated categories names, separated by dashes. An example would be *ST-SR-TA*, which represents a problem with robots that perform single tasks, tasks that require a single robot and prior knowledge of future tasks.

Korsah, Stentz and Dias [KSD] expand this taxonomy by an additional stage. They introduce four different categories to classify the degree of dependencies between the tasks:

- **No Dependencies (ND)**
- **In-Schedule Dependencies (ID)**
- **Cross Schedule Dependencies (XD)**
- **Complex Dependencies (CD)**

No Dependencies. The execution of each task is independent. This class can be used for many problems as a simplifying assumption. Even if a problem should show characteristics of dependencies, a first approach could be to assume the dependencies non-crucial to the solution of the problem and solve it as if the dependencies didn't exist. Even if the dependencies turn out to be important, such a simplified solution can often provide vital insights into the inner workings of a problem domain.

In-Schedule Dependencies. Tasks can have some sort of dependency on other tasks in the same schedule. An example for this problem class is any kind of spatially distributed task execution. Considering a robot must traverse some distance to get from one task to another, the cost function clearly depends on the order of task execution to some degree, as some tasks might be closer together than others.
Cross Schedule Dependencies. Dependencies can additionally exist between two tasks within the respective schedules of two different robots. This implies that the actions of one robot might also influence others. An example for this would be a general notion of precedence constraints. Let's consider a problem, which requires some tasks to be completed before others can be started, but does not require these tasks to be done by the same robot. In such a case it would be possible that one robot might have to wait to begin execution of a task until another robot finishes one of its prerequisites.
Complex Dependencies. For the previous classes tasks were meant to have a definite decomposition, meaning that if a task had a set of prerequisites for example all of them would have to be completed. In contrast complex dependencies might have a complex decomposition, where a task can have alternative prerequisites. Not all of these prerequisites must be completed, some subsets would already suffice. Additionally to task allocation and scheduling, this adds the challenge of selecting the optimal subset of dependencies within the decomposition tree.
Combining this additional level of interrelatedness with the original categories from Gerkey et al. the result would theoretically be $2^3 \cdot 4 = 32$ distinct problem classes. This total number is reduced however, by some combinations, which are impossible by definition. Such is the case with *ND [MT-SR-TA]* for example, multi-robot tasks as indicated by "MT" already implies some sort of task dependency on the schedules of multiple robots and thus cannot be classified as ND (no dependencies). After all such exclusions, Korsah et al. presents a total of 21 problem classes for their taxonomy.
An Illustration of the taxonomy structure and the resulting problem classes can be seen in figure 2.1.

Nunes et al. (2017) [NMMG] presents an alternative taxonomy, by the name MR-TA/TOC. It is also based on Gerkey's basic classes of ST/MT, SR/MR and IA/TA, but focuses specifically on temporal and ordering constraints, which might be imposed on the problem. This is accomplished by extending the category of time-extended assignment by two additional sub categories: Problems with *time window constraints (TA:TW)* or *synchronization and precedence constraints (TA:SP)*. Time window constraints refer to the fact that some mission goals are only achievable during a specific time frame during the execution of the plan. This presents a special case of a general time-dependency of the underlying problem. Synchronization and precedence contraints impose cross-schedule dependencies between the individ-

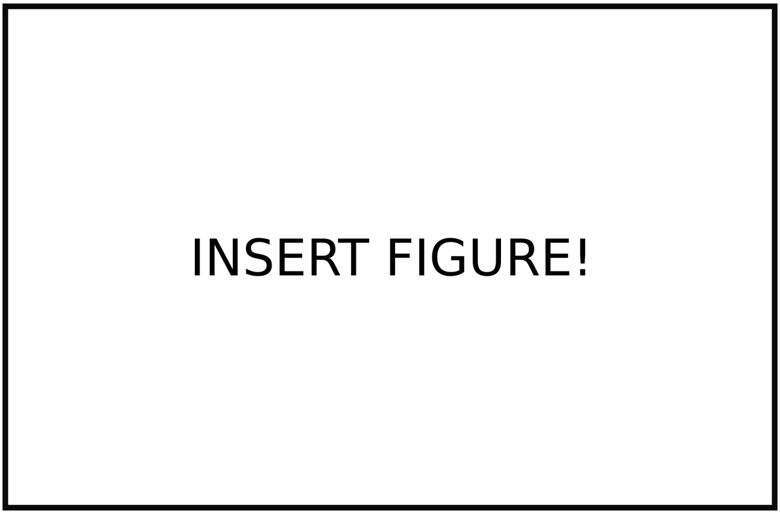

Figure 2.1: *Multi-Robot Task Allocation Taxonomy.* Description

ual tasks much like they are addressed in Korsah's taxonomy. General precedence constraints only require the termination of some task as the requirement for starting another task. The notion of synchronization adds an additional restriction to such a precedence relationship, where the end time of the preceding task has to be in a certain time interval relating to the start time of the following task.

2.2 Taxonomy of Routing Problems

The following section deals with the *Vehicle Routing Problem (VRP)*. Specifically this entails the introduction of the origins of the vehicle routing problems, it's early development within the research community and it's relationship to other similiar fields and topics. Thereafter more recent developments of the field are mentioned, specifically concerning the idea of *synchronization*, due to it's relevance to this thesis and the connection towards the MRTA. After that, some possible taxonomies for the field of VRP are showcased. The section ends with a comparison of MRTA and VRP taxonomies, which highlights the conceptual differences within the respective fields approaches.

2.2.1 The vehicle routing problem

Although the exact origin of the VRP is unclear, the "Truck Dispatching Problem" by Dantzig and Ramser (1959) [DR] is often mentioned as one of the earliest publications to introduce the general idea of the vehicle routing problem.
The VRP is an optimization problem which is related to the much more well known *Traveling Salesman Problem (TSP)*. The TSP can be described as follows: A set of spacially distributed cities is given and a traveling salesman has the intention to visit every city exactly once. The optimization objective is to find the route which includes all these cities and ends at the starting location, which minimizes the total travel distance between the cities. For a more detailed description of the TSP refer to Flood (1956) [Flo]. The VRP in turn is seen as an extension of the TSP. For the Vehicle Routing Problem[1]there is also a set of locations which have to be visited. Additionally it is assumed that there is one "depot" location which contains a fleet of vehicles. These vehicles are available to visit the required locations. The problem is additionally constrained in such a way that every location is only to be visited once by any vehicle and every vehicle has to return to the depot after it's last job. The objective of this problem is also to minimize the cumulative travel distance of all vehicles. The mathematical model for the VRP represents the customer locations as nodes in a network graph, where the edges between these nodes repesent the travel costs between locations. The problem is formulated as a *mixed integer problem (MIP)*, where a series of constraints enforces the above mentioned properties of a valid solution. For an illustrative example of a VRP solution refer to to figure ?.
For one thing, the VRP has been studied on a more theoretical basis as a mathematical optimization problem. (Do I want an example here? of an early theoretical paper for VRP) But it also had a very concrete practical implication: Due to it's structure, it served as a simplified model for distribution processes of the logistics industry. The vehicles would represent trucks and the locations would represent drop-off destinations for some goods. Subsequent improved solutions for the VRP would then go on and also improve planning for real life delivery problems. Examples for this could be

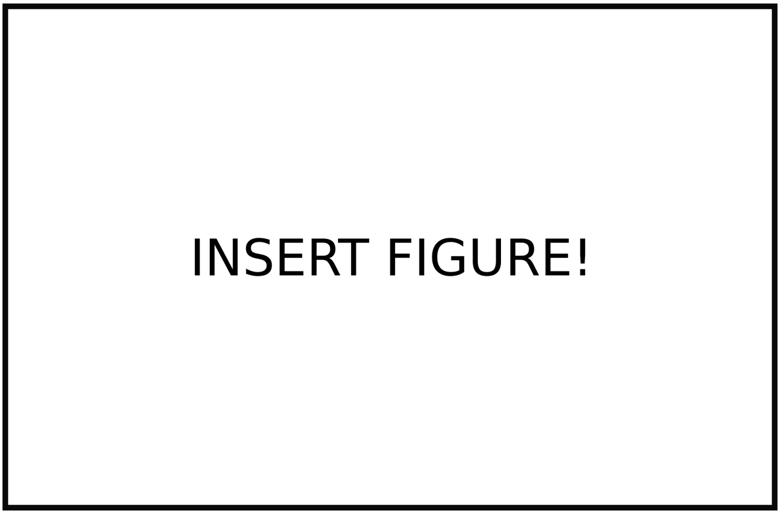

Figure 2.2: *Illustrative example of vehicle routing problem.* Description

seen by publications, which have applied the vehicle routing problem for newspaper distribution [?], milk truck routing [?] and SOME OTHER EXAMPLE [?] just to name a few. As the broader field delivery operations was the main application for the Vehicle Routing Problem in the earlier years, the requirements of these very operations have had a big impact in the creation and investigation of new VRP variants.

Arguably the most influential variant of VRP was the introduction of "time windows". This *Vehicle Routing Problem with Time Windows (VRPTW)* first off introduces a scheduling dimension to the previous routing problem. The start and end time of every visit and every vehicle are now being kept track off. This information is important because it is now also possible for a location to define a time window, where the starting time of a visit must lie in between a maximum and a minimum value. The practical importance of this addition is the fact, that in real life delivery applications customers often only have a limited availability. Solomon (1984) [Sol] presents a first in-depth analysis of time window aspect within vehicle routing. The author conducted a variety of computational experiments on a set of generated problem instances using custom heuristics.
Another important addition to the VRP was the principle of vehicle capacity. Within the *Capacitated Vehicle Routing Problem (CVRP)* each vehicles is also associated with a certain available capacity. The locations in turn also define a required capacity. For each vehicle the available capacity presents an upper limit towards the number or visits it is physically able to perform before having to return to the depot. An important variant for this thesis specifically is the *Heterogeneous Vehicle Routing Problem (HVRP)*. This generic terminology has been used to describe many different

variants of the VRP already. The commonality in those cases being the heterogeneity of one or more attributes of the vehicles or locations. Some common examples would be that different vehicles might have different properties such as travel speed or storage capacity. In some case visit durations are defined individually for different vehicles and sometimes visit locations are even exclusive to some specific vehicle type. Golden et al. (1984) [GALG] for example introduced the "fleet size and mix" vehicle routing problem. This is a subcategory of the heterogeneous VRP, which considers varying vehicle capcities for different vehicle types. Additionally the problem captures the idea of a variable fleet size, which can be summerized as follows: "If there is an infinite pool of vehicles available and routing costs drop with the number of vehicles, but every additional vehicle introduces a static cost, which is the optimal number of vehicles to use?". The paper developed several heuristic algorithms as well as a lower bounding procedure to tackle the problem.
A variant, which has been getting more attention more recently is the *Dynamic Vehicle Routing Problem*. For this it is necessary to understand the static and limited nature of the classic VRP: Let's say as an example a delivery company wants to employ the VRP as a model to optimize their routes for each work period. At the beginning of each day, a plan would be generated from the information about available vehicles, drop-off locations etc. Following the creation of the plan the vehicles would leave the depot to execute this plan. This means the application scenario would always be strictly divided into the planning phase and the execution phase. The dynamic VRP takes into account the fact, that in reality there are often unforeseen events or new information during the execution of a plan. It's basis is to investigate algorithms, which can modify plans following the revelation of new information about the system.

2.2.2 Routing problems with profits

The basic formulation of the vehicle routing problem such as given by [DR] or [GALG] only includes the minimization of the routing costs as well as the satisfaction of some capacity constraint. Additionally every customer node has to be visited. A related optimization problem is presented by the so called *routing problems with profits*. These kinds of problems introduce two changes to the VRP concept:

1. Only a subset of nodes can be visited.

2. Every node is additionally associated with a *profit*.

The optimization objective thus also includes the dimension of choosing the most suitable nodes. These chosen nodes have to fit both in terms of provided profit as well as expected travel cost. The *profitable tour problem (PTP)*, *price collecting traveling salesperson problem (PCTSP)* and the *orienteering problem (OP)* are some examples for this problem class. The major difference between them being whether the profit or the cost is implemented in the objective function or a constraint of the problem formulation. [VG]

From the above mentioned problems, the orienteering problem is the most well known. The problem's name originated from the sports game of "orienteering" (SOURCE?), where a player has to visit certain checkpoints and return to the starting location within given time frame to score points. At it's core the base OP is more similiar to the traveling salesman problem, because it only considers one vehicle. The objective is to maximize the profits, while there is an upper limit to the travel costs enforces by an additional constraint.
Like the VRP, the OP has spawned various variations and extensions over the years. The most commonly used extension, the *team orienteering problem (TOP)* considers a fleet of vehicles to be available. Other extensions include time windows [?], time depenent travel times and or profits as well as

For a detailed introduction to routing problems with profits refer to [VG] and for a survey of the literature see [VSO].

2.2.3 Synchronization in Vehicle Routing

Claim: The VRPTW with synchronization and precedence constraints is more difficult to solve then the normal VRPTW.
This claim is supported by Castillo-Salazar et al. [**?**]. In their work they conduct a computational study of the Workforce Scheduling and Routing Problem model proposed by Bredström and Rönqvist [**?**]. Several of Solomon's [**?**] classic VRPTW instances are adapted to include synchronization and precedence constraints. In one of their experiments they could show that a commercial MIP solver produces feasible solutions much more frequently when relaxing the additional synchronization constraints. Additionally the quality of the found solutions also improves significantly without the node interdependency.

2.2.4 VRP Taxonomies

Bodin and Golden (1981) [BG] present a taxonomy for vehicle routing and scheduling problems. The problem classification taxonomy includes a total of 13 categories. These categories cover a number of different attributes such as the nature of capacity constraints, the underlying network graph, vehicle heterogeneity and the objective function among other things. A particular emphasis is made towards the nature of temporal constraints. Three cases are identified for the different variations of available time frames to complete a task:

- The time of arrival is fixed in advance. The problem thus boils down to a pure *vehicle scheduling problem (VSP)*, as the only objective is to meet the tight timing constraints.

- Tasks define time windows of availability. The problem is classified as a *combined vehicle routing and scheduling problem (VRSP).*
- No timing constraints are imposed by the tasks. The problem is classified as a pure *vehicle routing problem (VRP)*

This differentiation implies, that VRSP would be the correct naming convention for every problem which includes some type of temporal aspect. Although this is sometimes the case, it is not used consistently throughout the literature. More often the term VRP is used to describe all kinds of variations inlcuding those with temporal constraints.
Bodin and Golden also introduce a basic classification for solution approaches, where they have identified 7 rough categories. These emphasize the different heuristic strategies, which have been used primarily at that time.

Desrochers et al. (1990) [DLS] developes a classification scheme for the VRP, which shares some common characteristics with [BG], but also significantly extends the scope. Notable extensions inlcude the possibility of multi depot and multi time window definitions, as well as synchronizations constraints. In addition to those extensions, a custom definition language is developed to accurately describe a certain configuration of those properties. Building on this definition language Desrochers et al. (1999) [DJL$^+$] introduces a "model and algorithm management system for vehicle routing and scheduling problems". This system aims to support the modeling process of physical distribution processes, as well as the selection and implementation of solution algorithms. Given a certain configfuration of problem parameters, the implementation of this decision support system provides a list of well known VRP related problems ranked by their degree of similiarity. This information about the similiar mathematical models and their solution approaches guides the process of implementing solution schemes for a custom problem variation.

Eksioglu et al. (2009) [EVR] conducts an exhaustive study of the existing VRP literature. The resulting taxononmy is based on Bodin and Goldens initial proposal, but greatly extends the scope and detail of both previously mentioned attempts. The taxonomy consists of five major categories, totaling 26 evalution criteria:

- **Type of study** refers to the type of publication. Types may differ as much as a purely computational study or a theoretical proof.
- **Scenario characteristics** includes all those characteristics, that are not a part of the constraints embedded into the solution, but part of the problem scenario.

- **Problem Physical Characteristics** summerizes the factors which directly affect the solution.
- **Information Characteristics** deals with the nature, accessibility and processing of the information about the problem. This may range between variations of static, dynamic and stochastic properties.
- **Data Characteristics** is used to classify whether or not data has been used in the context of a computational study, for example. It also addresses the origin of this data, which may be based on real world problems or computationally generated.

The approach differs from previous attemps by creating an evaluation scheme geared towards the VRP literature instead of just the problems. This can be seen with the categories "type of study" and "data characteristics", which are properties related to the publication from which a problem has originated from and not the problem itself.
A notable addition in respect to the previously mentioned approaches is the inclusion of "information characteristics" and thus the possibility of describing (partially) dynamic vehicle routing problems. However, the authors note about their own effort: "The current attempt to define a taxonomy for the VRP literaturemay have its own disadvantages but it does not suffer from ambiguity [...]. In fact, this taxonomy may be too detailed."(Eksioglu et al. Computers & Industrial Engineering 57 (2009) p.1477)

Lahyani et al. (2015) [LKS] presents a taxonomy consiting of two major categories and a total of 16 evaluation criteria. The major categories are called 'scenario characteristics' and 'problem physical characteristics' much like in Eksioglu et al., although the actual subcategories differ. This taxonomy also focuses on the specific problems rather than on the more general literature. It can be seen as an effort to reduce the complexity presented in the previous approach. Considerations of information characteristics are still maintained, albeit condensed into less, more generalized criteria.

2.2.5 Comparing MRTA and VRP taxonomies

The fields of multi robot task allocation and vehicle routing share various commonalities. At their core they are both mathematical optimization problems, which aim to create routes/schedules for a team of (mobile) agents to optimize some kind of cost or profit function. Despite their inherently similiar structure, they also have some notable differences. These differences also reflect in the respective field's approach to creating taxonomies. The following comparison is supposed to highlight those differences between the previously mentioned taxonomies of both fields, but also outline how some categories can still be related to one another.

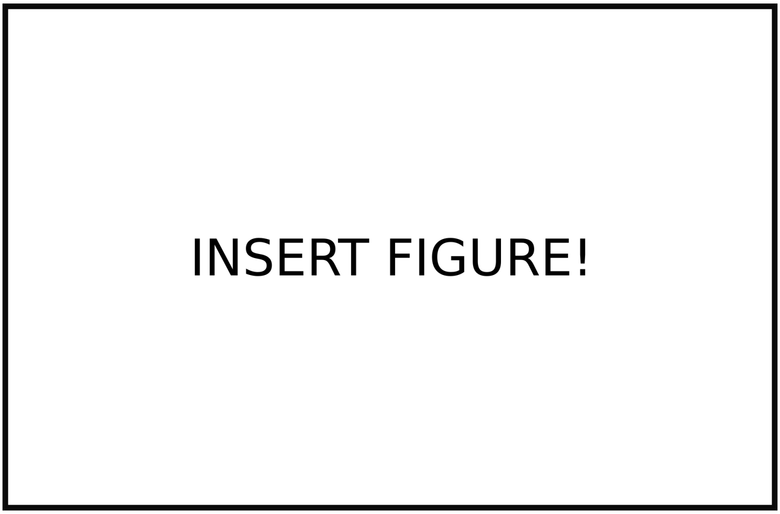

Figure 2.3: *Relationship between MRTA and VRP.* Venn diagram visualizing the relationship between the fields of multi robot task allocation (MRTA) and vehicle routing (VRP)

The most notable difference is in the granularity and generalization displayed within the taxonomies. The MRTA approach represented by Korsah et al. [KSD] focuses on a small amount of generalized categories thus resulting in a small amount of 21 possible combinations. The VRP approaches on the contrary have a lot of categories for very nuanced details of a problem, which in turn have multiple possible classification values. This goes as far as Eksioglu et al. having 26 evaluation criteria alone, each having around 2-6 possible values, resulting in a huge number of possible combinations. This is due to the fact that different application scenarios for physical distribution processes have introduced very specific constraints and variations over the years. The term VRP has been used to unite a lot of different ideas in the past and is thus arguably an inherently more generic term than MRTA.
In general the relationship between the two fields can be visualized by a venn diagram alike figure 2.3. Both fields have their own quirks, which are mostly exclusive to themselves, but also overlap in certain areas. As such Korsah's taxonomy lists several VRP publications as examples of it's categories and VRP models/algorithms are applied to robot routing and scheduling problems. A notable similiarity can be observed with the respective fields emphasis on temporal and synchronization constraints, as it is apparant with Nunes' MRTA/TOC taxonomy [NMMG] and the recent increased effort towards vehicle routing problems with synchronization constraints (sec.**??**).
Additionally many idea from the respective fields can be put into relation with each other illustrated by the following examples:

- The fact that agents can start at any location in a MRTA scenario can be seen a multi depot VRP.
- The idea of time-extended assignment of MRTA tasks describes the fact, that knowledge about the nature of tasks is known from the start, therefore this directly relates the to scenario of a static VRP. Instantaneous assignment on the other hand implies, that knowledge of tasks will be released only during the execution period. This can be roughly translated to the dynamic VRP, where additional knowledge may also inluence the system during execution.
- ...

2.3 Approaches for solving the multi-robot coordination problem

2.3.1 Instantaneous Assignment

Exact solution approaches

2.4 Approaches for solving vehicle routing problems

2.4.1 Metaheuristics

Single solution based

Population based

Hybrid metaheuristics

2.4.2 Exact solution approaches

Branch and Bound

2.4.3 Human-Machine-Interaction

Human-centric approaches

Machine-centric approaches

2.5 Related Work

2.5.1 Home Health Care

2.5.2 Technician Scheduling

2.5.3 Manpower Allocation

2.5.4 Worforce Routing and Scheduling

2.6 Existing solutions

The following section showcases selected, concrete approaches from existing VRP literature, which exert favorable attributes for being applied to the subject multi robot coordination problem.
At first, two sub-areas of the well known VRP are presented in sections 2.5.1 and 2.5.2. These areas will be highlighted due to their collective recent focus on synchronization constraints, as presented in section 2.2.3.
Then individual publications and their approaches will be showcased and compared in respect to their implementation of the favorable attributes. These favorable attributes being the ones identified in section [?] as crucial for a most complete representation of the multi robot coordination problem motivated by planetary exploration and mission planning. These criteria include the possibility of cooperative task execution, precedence constraints and agent heterogeneity.
The section will close with an evaluation of the presented literature and their characteristics. Based on this evaluation of the the presented approaches, one will be chosen for further investigation within this thesis.

2.6.1 Comparison of selected approaches

This selection of publications has been made based on their varying degrees of sophistication regarding the criteria of homogeneity, cooperativity, precedence, objective function, time windows and algorithm performance. The presented subset is not assumed to be complete. Some problem characteristics and/or approaches are vastly widespread in the broader field of VRP literature. For such cases, presenting all or even multiple possible solutions would exceed the scope of this comparison. Furthermore, in such a case the chosen publications are exemplary for the characteristics of their respective fields.
The selection does however contain all the singular outstanding publications, which have revealed themselves to be the most promising subjects regarding an adaption to the multi robot problem.

Bredström and Rönnquvist [**?**] present a MIP model formulation for the Vehicle Routing and Scheduling Problem with time windows and additional temporal constraints. By doing so they are one of the first to introduce the idea of pairwise synchronization and precedence constraints to the vehicle routing problem. They argue, that temporal dependencies between tasks are more expressive in describing real life problems. As an example they mention the issues of homecare staff scheduling and forest operations, which both exert strong requirements of task interdependency. The problem is solved using a MIP-based decomposition heuristic.
Rasmussen et al. [**?**] consider the Home Care Crew Scheduling Problem with soft

preferences and temporal dependencies. In this problem a set of home carers, such as nurses, has to be assigned to a given set of services at patients homes to minimize the total operational cost as well as negative patient preference for individual home carers. Pairwise synchronization and precedence constraints are considered between services. A Branch-and-Price algorithm is developed to solve smaller instances to optimality. For large instances preference-based visit clustering is employed to reduce problem complexity and thus computational time.

In Mankowska et al. [?] the problem of Home Health Care Routing and Scheduling is also investigated. Pairwise synchronization and precedence are also considered, although allowing only a maximum of two interdependent services per node/patient. Additionally they consider home carers with heterogeneous sets of qualifications, but no patient preferences. They propose an Adaptive Variable Neighborhood Search algorithm, which adjusts the search tree exploration strategy specific to the concrete problem instance.

Ait Haddadene et al. [?] also work on the problem of Home Health Care Routing and Scheduling. Aside from preferences and temporal dependencies, heterogeneous qualifications and multiple service patients are used for the model. They evaluate GRASP and ILS metaheuristics as well as a hybrid approach of the former for solving the proposed MIP model and confirm the hybrid algorithm to be superior to the single solutions.

In a different work [?] the same researchers investigated the problem using a true multi-objective approach to simultaneously optimize the total travel time of home carers as well as patient preferences. They employed different variations of the Non-dominated Sorting Genetic Algorithm enhanced with local search to solve the bi-objective problem. The conclusion yields, that while the approach efficiently solves the problem, no substantial improvement could be made.

Lasfargeas et al. [?] try to solve the home Home Health Care problem with temporal synchronization and precedence between tasks as well. Aside from worker qualifications they also introduce hard patient as well as worker preferences. They argue, that both patients as well as workers might have incentives to refuse some workers and patients respectively. For patients social embarrassment regarding nurses of the opposite sex would be an example. Likewise nurses suffering from serious allergies could avoid visiting the homes of pet owners. The objective is to minimize a weighted sum of all the job starting times, and time window violations, while also considering worker break time regulations. A possible solution to the problem is provided by a novel construction heuristic and a Variable Neighborhood Search metaheuristic.

Manavizadeh et al. [?] propose a MILP model for the Home Health Care Problem which considers staff qualification and multiple interdependent services per patient. In this case the problem is also designed with an unlimited number of possible home carers. For each additional home carer employed in the final schedule a fixed cost is added to the overall objective function. So aside from minimizing the total travel

cost and time window violation the objective also considers to minimize the total amount of home carers required. A big part of of the work is dedicated to a sensitivity analysis of the proposed model in regards to several instance parameters. A commercial solver is used for small and medium sized problem instances and a Simulated Annealing algorithm is devised to solve larger instances.
The model proposed by Entezari and Mahootchi [?] also supports temporal precedence and synchronization, as well as worker qualifications for the Home Health Care Problem. The objective function included terms for total travel distance, time window violations, home carer working hour violations and patient preferences. Additional constraints are introduced to support break time regulations for workers and optional retrieval of blood samples from the patients homes. A genetic algorithm is developed to solve the problem.

Korsah et al. [?] introduce a MIP model for the Vehicle Routing Problem, which handles task synchronization and precedence, heterogeneous vehicle capabilities and location choice. The application of the proposed model is motivated by disaster preparedness planning. In the case of a natural disaster support vehicles can be routed efficiently to provide medical attention and evacuate the population. The novel addition of location choice introduces the idea that a given task does not have to be performed at a single location, but at a set of possible locations. An optimal solution algorithm based on the branch-and-price framework is developed to fit the specific model.
Tao et al. [?] is motivated by transporter scheduling for assembly blocks in a shipyard. The problem is modeled as a multiple Traveling Salesman Problem with synchronization and precedence constraints. Transport vehicles are however modeled with homogeneous capabilities. The objective is to minimize a total of all transport, delay and waiting times. A hybrid Genetic algorithm and Tabu Search subprocedure is developed to solve the problem.
Firat and Hurkens [?] present a model for the Multi-Skill Technician Task Scheduling Problem, in which a set of technicians with heterogeneous skill levels in different domains is partitioned into teams on a daily basis to complete a set of tasks. These tasks may require varying degrees of skills and they may define precedence relationships towards other tasks, as well as priorities. The most notable difference of this approach to all previously mentioned is that neither a spatial routing aspect nor time windows are considered for the problem. A combinatorial algorithm is developed for the model. This approach brought forth the best overall solutions for the ROADEF challange [?]
Pereira et al [?] also work on an extension of the TTSP, denoted Multiperiod Workforce Scheduling and Routing Problem. They introduce a routing aspect to the original scheduling problem by defining travel distances as arc weights in a graph of task nodes. Tasks may consist of subtasks, which can define precedence rela-

Publication		Characteristics			Computational tests	
Reference	Year	Field	Approach	Optimal?	$\lvert N\rvert^{(a)}$	Instance origin
[?]	2008	Home Health Care	MIP heur.		80	random
[?]	2012	Home Health Care	BnB	✓[(b)]	150	real world data
[?]	2014	Home Health Care	AVNS		300	random
[?]	2016	Home Health Care	NSGAII		73	[?]
[?]	2016	Home Health Care	GRASPxILS		73	[?]
[?]	2019	Home Health Care	VNS		300	[?]
[?]	2020	Home Health Care	SA		250	random
[?]	2020	Home Health Care	GA		50	random
[?]	2010	Disaster response	BnP	✓	20	random
[?]	2019	Construction	GAxTS		50	random
[?]	2012	Technician Scheduling	Constr. heur.		800	[?]
[?]	2020	Technician Scheduling	ACO		100	random

Table 2.1: *Overview of selected publications.* The table shows the following columns enumerated from left to right: (1) A reference to the specific paper, (2) the year it was published, (3) an abbreviation for the name of the problem which was addressed in the paper, (4) the name of the algorithm/approach used to solve the problem, (5) whether or not optimal solutions could be produced with this approach, (6) the number of nodes for the largest studied problem instance and (7) the origin of the problem instances used.

[(a)] It is important to note, that the problem complexity is dependent on a multitude of other things beside the number of nodes. Examples would be the number of vehicles and the density of synchronized visits. The parameter for the amount of nodes presented here is only meant to provide a first impression of the problem complexity.

[(b)] An optimal algorithm is developed, but to reduce computational times it is extended wit a heuristic clustering method for larger instances, thus loosing optimality.

tionships. Additionally these subtasks can also define skill requirements for the processing team, although team composition is assumed to be fixed throughout the multiperiod planning horizon. The objective is to minimize the final day of the schedule. A novel construction heuristic along with multiple variations of the Ant Colony Optimization metaheuristic are evaluated for their effectiveness for solving the problem.

Table 2.1 provides an overview of the selected publications. For each presented work it contains the information about which problem is to be solved, the chosen approach to solve the problem and whether or not this approach is able to produce optimal results. Additionally some information about the computational testing is provided with the number of nodes within the largest processed problem instance and the origin of the used set of problem instances.

From this overview some initial observations can already be made:

Instance sizes. Problem instances for computational testing tend to be comparably small with a cap of 300 nodes. Only Firat and Hurkens [?] presents itself as an outlier, managing up to 800 tasks within the biggest instance. Regarding this specific paper, it has to be emphasized that the underlying problem studied in their work is

purely scheduling based and does not contain a routing component.
Heuristic approaches. Most of the relevant literature seems to prefer heuristic and metaheuristic approaches over those with the capability to provide globally optimal solutions. The two approaches presented here which actually do implement optimal procedures, namely [?] and [?], are only able to handle even smaller problem instances. Korsah et al. [?] only handles instances with up to 20 nodes. Rasmussen et al. [?] indeed handle larger instances with a size up to 150 nodes, although only by using a clustering-enhanced branching scheme and thus loosing global optimality.
Problem instances. Regarding the origin of the problem instances used for computational testing there are mainly two basic options: Using real world data, which was provided for example by an actual home health care provider, or randomly generating data sets. Most often, the random generation of data sets is also designed in such a way that the final results best reflect actual circumstances for the motivated real life domain. This could for example include a certain spatial clustering of nodes or a specific ratio of single versus synchronized visits. Within the reviewed literature this generation of data seemed to be the more popular choice.
Another prominent option for handling computational tests is to use instances from other publications. This is often done to be able to compare the performance of a new algorithm to other earlier solutions within the literature in respects to objective function value and/or computational time. For this aspect it can be noted that both the original instances of Bredström & Rönqvist [?] and Mankowska et al. [?] have occasionally been reused throughout more recent publications.

Precedence and Cooperativity

The following section will compare the selected publications regarding their characteristics of precedence and cooperativity.
The criteria of precedence describes the ability of an approach to be able to handle additional constraints, which link two or more tasks into a precedence relationship. One such constraint expresses the need that certain tasks need to be started or completed before work on another task can start.
[KSD] The criteria of cooperativity, in the following used synonymously with the term *synchronization*, refers to the potential need of one or more robots cooperating to solve a task together. Including this option opens up a myriad of possibilities for problem solving. Especially in combination with heterogeneous robot fleets, this enables the cooperation of multiple specialized abilities to perform more complex tasks.

	Cooperativity				Precedence		
reference	at all?	between nodes?	>2?	Team building?	at all?	between nodes?	$\delta_{min}, \delta_{max}$
[?]	✓	✓	✓		✓	✓	✓
[?]	✓	✓	✓		✓	✓	✓
[?]	✓				✓		✓
[?]	✓		✓		✓		✓
[?]	✓		✓		✓		✓
[?]	✓	✓	✓		✓	✓	✓
[?]	✓	✓	✓		✓	✓	✓
[?]	✓	✓	✓		✓	✓	✓
[?]					✓	✓	
[?]	✓	✓	✓		✓	✓	
[?]	✓		✓	✓	✓	✓	
[?]	✓				✓	✓	

Table 2.2: *Precedence and Cooperativity characteristics of selected publications.* Columns of the table contain the following content (enumeratied from left to right): (1) A reference to the publication in question (2) If there is any concept of cooperativity (3) If cooperative task execution is defined between pairs of nodes (4) If cooperative behaviour can include more than two robots (5) If cooperativity is implemented by team building (6) If there is any concept of precedence (7) If precedence relationships are defined between nodes (8) If the precedence formulation includes a minimum and maximum starting time distance

Heterogeneity

Secondary Criteria

2.6.2 The case of exact methods

2.6.3 Evaluation

2.6.4 Complete Overview

	Heterogeneity						
		Preferences				Skill matching	
Reference	At all?	hard	soft	V to N	N to V	binary	levels
[?]	✓		✓		✓		
[?]	✓		✓		✓	✓	
[?]	✓					✓	
[?]	✓		✓		✓	✓	
[?]	✓		✓		✓	✓	
[?]	✓	✓		✓	✓	✓	
[?]	✓		✓		✓	✓	
[?]	✓		✓		✓	✓	
[?]	✓		✓			✓	
[?]	✓						
[?]	✓					✓	✓
[?]	✓					✓	✓

Table 2.3: *Heterogeneity characteristics of selected publications.* Columns of the table contain the following content (ltr): 1) The reference to the publication in question. Whether preferences have been considered as 2) hard constraints or as 3) soft constraints. Whether preferences are considered as 4) A vehicle prefering certain nodes or 5) A node prefering certain vehicles. Wether skill matching is considered as 6) binary (a skill requirement is either fullfilled or not) or as 7) different skill levels

Reference	Approach	Primary Criteria										Secondary Criteria				
		Optimality	Cooperativity			Precedence			Heterogeneity			Time windows		VRP char.		Instances
		Global	At all	Nodes	> 2	At all	Nodes	$\delta_{min}, \delta_{max}$?	At all	Pref.	Skills	Hard	Soft	Limited	All nodes	Size
[?]	MIP heur.		✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	M
[?]	BnP	(✓)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		L
[?]	AVNS		✓			✓		✓	✓		✓	✓	✓	✓	✓	L
[?]	NSGAII		✓		✓	✓		✓	✓	✓	✓	✓		✓	✓	M
[?]	GRASPxILS		✓		✓	✓		✓	✓	✓	✓	✓		✓	✓	M
[?]	VNS		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	L
[?]	SA		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	L
[?]	GA		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	M
[?]	BnP	✓				✓	✓		✓	✓	✓	✓	✓	✓	✓	S
[?]	GAxTS		✓	✓	✓	✓	✓					✓	✓	✓	✓	M
[?]	constr. Heur.		✓		✓	✓	✓		✓		✓			✓		XL
[?]	ACO		✓		✓	✓	✓		✓		✓			✓	✓	M

Table 2.4: *Characteristics summary of selected publications* The columns contain the following information (ltr): 1) The reference to the publication in question. 2) An abbreviation of the algorithmic approach used to solve the problem. 3) Whether the approach is able to produce globally optimal solutions. 4) Whether there is a sense of cooperativity at all, which 5) is formulated on a node/task basis and which 6) Is able to support cooperation of more than two agents. 7) Whether precedence is considered, which 8) is defined between nodes/tasks and which 9) is defined using a minium/maximum startung time offset formulation. 10) Whether agent heterogeneity is considered, which presents itself as 11) heterogeneous preferences between different nodes and vehicles and/or as 12) Skill matching of vehicle abilities to task requirements. Whether 13) hard or 14) soft time windows are considered. 15) Whether the fleet size of available vehicles is considered as fixed and 16) Whether the problem formulation includes, that all tasks have to be processed. 17) The size of the biggest considered problem instance, which the approach was able to handle, with S being up to 20 tasks, M being up to 100, L up to 250 and XL up to 800.

Chapter 3

Theory

3.1 Combinatorial Optimization

3.1.1 Mixed Integer Programming

3.2 Local Search in Routing

3.3 Evolutionary Algorithms

Chapter 4

Computational Results

4.1 Investigating the objective function

4.2 Genetic Algorithm Improvements

4.2.1 Population Size

4.2.2 Select Operator

4.2.3 Construction Heuristic

4.3 Sensitivity Analysis

4.3.1 Problem Size

4.3.2 Cooperation Constraints

4.3.3 Precedence Constraints

4.3.4 Degree of Heterogeneity

4.4 Friedmann Test

4.5 Evaluation Criteria

Chapter 5

Summary and Outlook

5.1 Discussion

5.2 Conclusion

5.3 Future Work

Appendix A

erster Anhang

Hier können weiter Graphiken oder Ähnliches als Anhang aufgeführt werden. Ebenso sind Untergliederungen der einzelnen Anhang-Kapitel möglich

text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text

A.1 erste Untergliederung

text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text text

IRS Institut für Regelungs- und Steuerungssysteme
Institutsleiter: Prof. Dr.-Ing. Sören Hohmann

Figure A.1: Abbildung im Anhang

A.2 Quellcodes

Quellcodes lassen sich gut mit dem listings-Paket einbinden, so ist das Einbinden von entsprechend formatiertem Matlab-/C++/etc.-Code ohne Copy/Paste direkt aus der Quellcode-Datei möglich. Und hier noch ein Beispielhafter Matlab Quellcode:

```
%% State Space System
asyn.SS = ss(asyn.A,asyn.B,asyn.C,asyn.D);

```

```
% Infos über das System
disp('- Informationen über das System -');
% Ordnung des Systems
asyn.n = rank(asyn.A);
disp(['Ordnung des Systems n = ', num2str(asyn.n)]);
% Polstellen
asyn.PS = pole(asyn.SS);
% Nullstellen
asyn.NS = tzero(asyn.SS);
% Beobachtbarkeit
asyn.Ob = obsv(asyn.SS);
if rank(asyn.Ob) == asyn.n
    disp('System vollständig Beobachtbar');
else
    disp('System nicht vollständig Beobachtbar');
end
% Steuerbarkeit
asyn.Os = ctrb(asyn.SS);
if rank(asyn.Os) == asyn.n
    disp('System vollständig Steuerbar');
else
    disp('System nicht vollständig Steuerbar');
end

disp('------------------------------------------------');
```

Listing A.1: Ein wahnsinnig komplizierter Quellcode

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