Supporting Sensor Scheduling in Intelligence

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***Abstract*—In this publication a two-step approach for resource-optimal sensor scheduling in intelligence is presented. This approach has been developed in close cooperation with subject-matter experts from the Intelligence, Surveillance, and Reconnaissance (ISR) domain. It constitutes the fundamental basis of a computer-aided assistance system for ISR management personal.**

I. Introduction

In light of the increasing complexity and diversity of today's threats, making the right decisions and initiating the right reactions becomes more and more a question of maximizing the benefit of ISR systems. To make this possible, interoperability and coordination between organizations and nations are required. Synergistic effects resulting from the application of data and information fusion have to be exploited optimally. One of the most essential perquisites to reach this aim is that the available sensors and their corresponding carriers are used with maximal efficiency and effectiveness to meet the need for information as completely as possible and to gain data and information being of the best possible quality with regard to the tasks at hand. Sensor and their corresponding carriers possess different characteristics and usually only certain sensor/sensor carrier combinations are actually suitable for obtaining a certain piece of information being requested. At sensor scheduling, there are also additional constraints that have to be taken into account, for example restrictions with regard to the actual availability and the endurance of the sensor/sensor carrier combinations. Usually, the set of available sensor/sensor carrier combinations is in total not sufficient to operate all information requests, such that these requests must be taken into account in a prioritized manner.

The operational context of the sensor scheduling problem considered in this publication is collocated with force commands at the strategic and operational level, both in national as well as in international force deployments, for example when NATO conducts Joint/Combined operations. The respective deployment of sensors and their specific carrier platforms results from a dedicated process, the Collection Coordination and Information Requirements Management (CCIRM) process. The fundamental elements of the CCIRM process are formulated in [1], the reader is also referred to [2], [3], [4] for descriptions of related processes. The CCIRM process is part of the Intelligence Cycle, a structured process consisting of different phases (Planning & Direction, Collection, Processing, Analysis & Production, Dissemination) that in essence creates intelligence by processing data and information [5].

It is important to note that within the sensor scheduling task being addressed by the CCIRM process, no detailed mission planning including also the derivation of optimal configurations of specific sensor/sensor carrier combinations as considered for example in [6] is conducted. Instead, detailed mission planning is part of the Recce Cycle (see for example [4]) being of course closely interrelated with the Intelligence Cycle regarding this aspect. Here, detailed asset mission planning is done based on the collection tasks having been derived by the CCIRM process.

At the German armed forces as well as at the allied armed forces, the ISR manager is responsible for the sensor scheduling task being addressed by the CCIRM process. This planning task is very challenging to the ISR manager and requires for assistance systems to support the ISR managers' decision making process. This holds true for preplanning tasks where sensor deployments are preplanned for a certain period of time. It even more applies to situations that cannot be predicted beforehand, for example for Troop in Contact (TIC) situations. However, up to now, only rudimentary means (like MS Excel, whiteboards ...) are available to support this demanding task.

To close this gap, we developed a two-step approach for resource-optimal sensor scheduling that will be presented within this publication. This approach has been developed in close cooperation with subject-matter experts from the ISR domain. It constitutes the fundamental basis of a computer-aided assistance system for ISR management personal being currently realized as a system demonstrator. While this publication aims at giving an overview on the approach in total and the relevant operational aspects, further publications will give more detailed insight into the underlying mathematical and computational details.

II. Operational Context

Figure 1 schematically illustrates the CCIRM process as part of the Intelligence Cycle. The CCIRM process is triggered after the Commanders' Critical Information Requirements (CCIRs) have been defined. The Intelligence Requirements Management (IRM) process, a sub-process of the CCIRM process, further gradually refines the CCIRs into a more fine grained hierarchy of information requirement specifications. This hierarchy comprises the Prioritized Information Requirements (PIRs), their subsequent refinement into Specialized Information Requirements (SIRs) and ends up in the definition of Essential Elements of Information (EEIs) corresponding to very fine grained information requirement specifications. For each EEI, one or more dedicated Collection Requirements

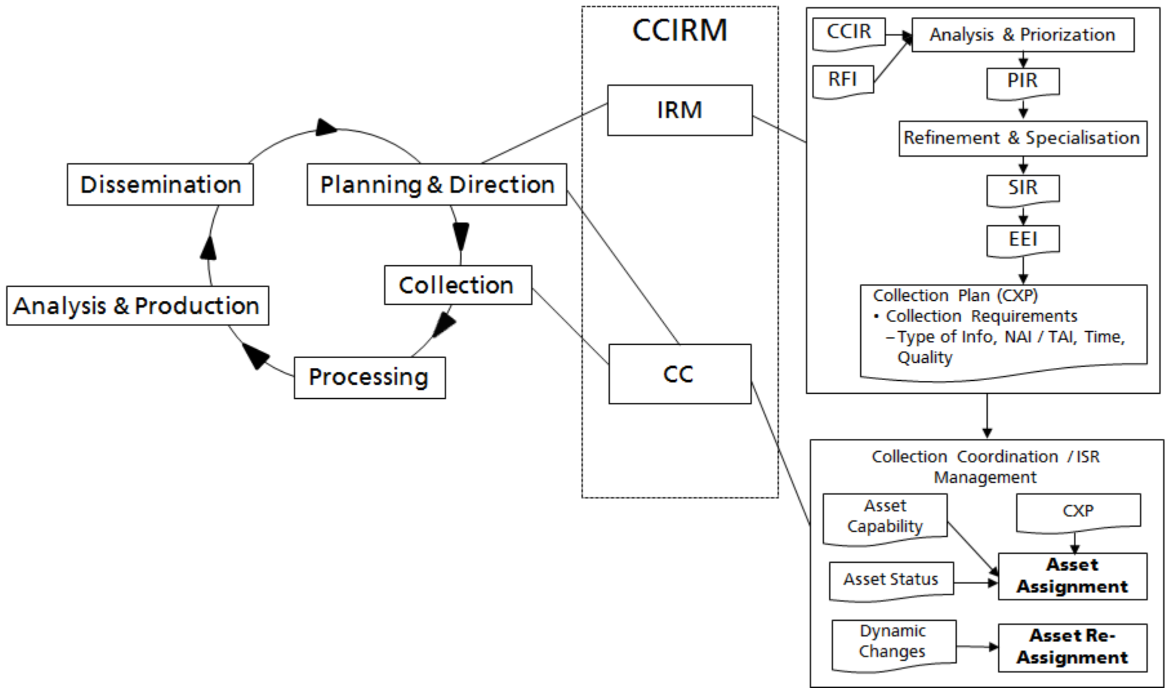

Fig. 1. Schematic illustration of the CCIRM process (right side) and its relation to the Intelligence Cycle (left side) .

(CRs) are derived afterwards. A CR further refines an EEI and defines which kind of information at which quality is required and puts them in relation to space and time. The first relation is for example established by assigning a dedicated Named Area of Interest (NAI) to each CR.

CRs act as an input to another CCIRM sub-process, the Collection Coordination (CC) process. Within this sub-process, the CRs have to put into effect in a sense, that the ISR manager triggers the information acquisition by use of specific sensors and their carrier platforms (assets). In order to identify suitable assets, he has to match the requirements originated from the CRs with capabilities and constrains of sensors and platforms available along with target characteristics. Within this matchmaking or planning phase, it is essential for the ISR manager to be able to react to dynamic changes during running operations, for example due to the loss of certain platforms, if necessary. This may require dynamic rescheduling of assets from low priority targets to high priority targets.

III. Two-Step Approach for Resource-optimal Sensor Scheduling

In-depth analysis of the relevant operational processes and the feedback obtained from workshops conducted with operational subject-matter experts from the military ISR domain clearly revealed the need for computer-aided assistance systems in order to support the ISR personnel in matching sensors and their corresponding carriers to the surveillance and reconnaissance targets deduced form the commander's information needs, even taking into account the actual prevailing conditions of the current operation and their potential changes over time.

A computer-aided assistance system supporting this task has to be designed in a way that the process of asset selection, assignment and scheduling itself as well as the results obtained by it are transparent and understandable to the user. Furthermore, one has to take under consideration the fact that certain selection criteria applied in practice cannot be adequately formulated in pure mathematical terms. This fact is orthogonal to the complexity of the resulting mathematical models representing the selection criteria and their relations.

Based on these facts and taking also into account the inherent high computational complexity of suitable algorithms for solving the underlying combinatorial problems regarding asset selection, assignment and optimization, a two-step approach has been worked out. This approach aims to support the matchmaking between sensors and dedicated carriers and the corresponding surveillance and reconnaissance targets as well as the scheduling of selected assets. It is schematically illustrated in Figure 2 and described in the rest of this section. In course of this description, also relations to similar approaches from the technical literature are highlighted.

Step One comprises an interactive pre-selection and suitability test of assets being in principle appropriate for serving the individual targets. This step is applied individually for each target that has to be considered at the task of ISR asset selection, assignment and scheduling. Pre-selection and test are based on technical and organizational capabilities of assets and target characteristics along with current operation conditions. Selection criteria may include target coverage of the sensors, environmental conditions, mission threats to assets, range to target, platform and sensor range standoff capability, system timeliness etc. The output of this step is a set of assets for

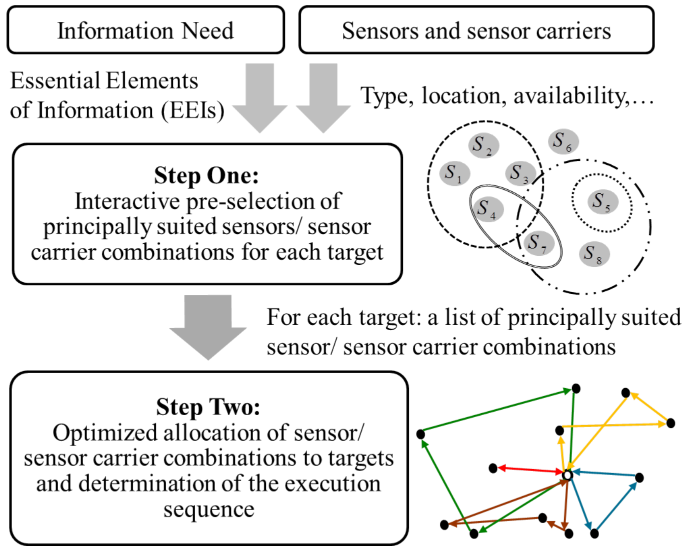

Fig. 2. Schematic illustration of the two-step approach for resource-optimal sensor scheduling. At Step One, for each target, the set of available assets (S) being principally suited according to certain selection criteria is determined sequentially. Step Two aims to derive concrete proposals which assets have to be finally assigned to which targets and the dedicated routes individual assets have to follow in order to serve these targets.

each target corresponding to a preliminary assignment of zero ore more assets being in principle suitable for serving the corresponding target. This preliminary assignment provides the input for Step Two, triggering an automated planning and optimization process.

In order to realize Step One, the concept of a sequential filter chain has been worked out. Within this concept that is also schematically illustrated in Figure 3, individual filters function independently from each other on the set of available assets. Each filter realizes a specific pre-selection/test criterion with regard to the target under consideration. The individual filters are applied sequentially. Thereby, they can be concatenated in a flexible fashion according to different mission needs. Subsequent application of the filters via the filter chain will reduce the set of assets being considered as in principle appropriate for the considered target step by step. Across all filters, the key input data represents the set of assets that are currently considered as being in principle suited for the target at hand. The output data represents the set of assets that are still considered as being in principle suited for the target at hand after the pre-selection/test criterion realized by the corresponding filter has been additionally taken into account. Having applied Step One on each target that has to be considered at ISR asset selection, assignment and scheduling, all the data necessary for running Step Two is gathered.

The idea behind Step One has some similarities to the work presented in [7] where also a knowledge based approach for matching assets to missions is presented. However, our concept of a sequential filter chain involving distinct interactive elements (for example also plausibility checks being requested to the user) is different with regard to essential details. Having the aim to support the user regarding the most essential elements of the pre-selection task and to ensure simple maintainability in practice, our approach is intended to be more light-weighted than the approach presented in [7]. In addition, a substantial difference is also that the results of Step One are primarily intended to serve as input for Step Two of the two-step approach for ressource-optimal sensor scheduling where the matching of assets and targets is further refined while the work presented in [7] addresses rather a stand-alone solution.

Step Two comprises the automatic planning and optimization process on assets and targets in space and time. In detail, this step aims to derive proposals which assets have to be finally assigned to which targets and the dedicated routes individual assets have to follow in order to serve these targets. The planning and optimization takes into account specific constraints such as time-windows, target priorities, specific asset capabilities required by the individual targets etc. In addition, it tries to optimize specific cost factors such as the minimization of the assets withdrawal time on target arrival, the minimization of the overall operation time of the assets fielded and the maximization of target being served in total, to name a few. The transparency and computability of the applied planning and optimization algorithms is greatly increased due to the pre-selection conducted in Step One.

In order to realize Step Two, a purely mathematical problem formalization corresponding to an optimization problem involving certain constrains has been worked out. A preceding formal problem analysis clearly indicated that the problem at hand possesses distinctive similarities to certain problem classes considered in the Operations Research domain, in particular to routing problems like Vehicle Routing Problems (VRPs) and Team Orienteering Problems (TOPs). Using these similarities, a mathematical model corresponding in essence to a routing problem that has been adapted where necessary to take into account the specific characteristics of the problem at hand has been worked out. Also for the solution of the corresponding optimization problem under constraints, well-

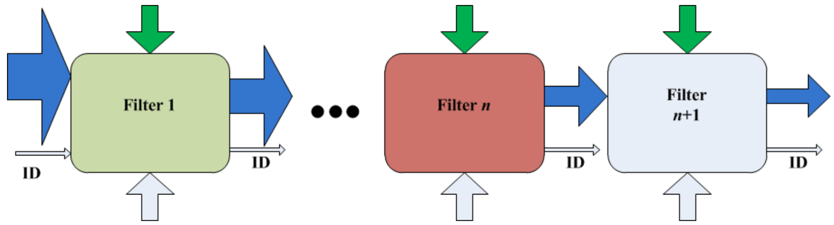

Fig. 3. Principle of the filter chain applied in Step One. Key input data and output data of each filter are sets of assets (blue arrows). Applying the pre-selection/tesk criterion realized by a filter will usually reduce the cardinality of an assets set (indicated in the figure by the decreasing size of the blue arrows). Additional input data (green and gray arrows) for a filter may be data representing specific parameter realizations or parts of the concrete context like weather conditions, daytime, etc..

founded State-of-the-Art algorithms from Operations Research domain have been adapted.

A literature review with regard to the approach intended for Step Two delivered that approaches being very similar but addressing different specific objectives have been described in [8], [9], [10]. These related works indicate the high potential of the intended approach based on an adaption of routing problems. However, to model the concrete operational aspects to be considered within this publication, a fundamentally new mathematical problem description had to be worked out.

IV. Automatic planning and optimization process

This section will focus on Step Two of the two-step approach for resource-optimal sensor scheduling that has been introduced in Section III. Thereby, it is assumed that Step One successfully revealed suitable asset-to-target assignments.

Section IV-A describes the elements of the corresponding planning problem including their relations and the corresponding planning dimensions for Step Two from an operational perspective. These findings have been verified in workshops conducted with operational subject-matter experts from the military ISR domain. In Section IV-B, the corresponding mathematical problem description and the concrete means for its solution are described.

A. Operationally relevant elements

At Step Two, the focus of the ISR managers' task is the consistent and optimized assignment between assets and targets during the planning period under consideration which includes still a further matching of selected target requirements against selected asset characteristics. The results obtained are dedicated routes per asset indicating the sequence in that the targets being assigned to this asset have to be served. It is important to note that the inferred routes have to be understood as some kind of a plausibility check for the adjacent collection tasking to be done by the ISR manager rather than as detailed asset mission planning (compare also Section I).

Each route starts from the home base the corresponding asset is deployed to and also ends in this home base. Within our current model, assets are not yet allowed to return in between to their home base for example due to recovery reasons but enabling this will be a topic for further research. In the operational ISR business, it is very common that the amount of targets exceeds the amount of (suitable) assets being available. This fact requires that a potential solution regarding the assignment between assets and targets during the planning period must be still considered as being valid even if not all targets have (suitable) assets assigned. To appropriately address this fact, it is essential to allow for different target priorities during the problem-solving process and to permit the definition of a certain threshold level for the priority, stating that a target with a priority exceeding this level must be served. It is remarked that missing assignments provide useful information to the ISR manager regarding the potential allocation of additional reconnaissance and surveillance resources during a running operation.

In Step Two of our approach, it is necessary to distinguish between hard and soft constraints that have to be considered at deriving the assignment between assets and targets during the planning period under consideration. Hard constraints represent restrictions that must not be broken by a potential algorithm realizing an automated planning component. The set of hard constrains includes for example the well-formedness (consistency) of the inferred routes. Weak constraints represent conditions that may be broken by the algorithm in order to find a valid solution. This set of constraints includes for example the demand that, optimally, each target should be served by a suitable asset – which is often not possible in reality (see above). Breaking weak constraints still produces valid solutions but usually lowers the overall solutions quality.

From the operational perspective, a target (in more detail: a surveillance target or a reconnaissance target) is in essence characterized as follows:

- Each target, in conjunction with its designated EEI, possesses a geographical location represented by its dedicated NAI. Thereby, the NAI corresponds to a geographical area, a point, or a line string.
- Each target possesses a certain priority assignment that is derived from the corresponding EEI. The higher the target priority, the higher is the relevance of this target with regard to operational issues.
- Each target requires certain collection disciplines (for example IMINT, SIGINT, etc.) in order to obtain the required data. In our current solution, we simplify this condition by making the assumption that each target requires exactly one collection disciple which implies that only one sensor platform with its specific sensor capabil-

ity pack is sufficient in order to solve the corresponding data acquisition task. This is a simplification in contrast to reality because in real world operations, often multiple collection disciplines have to be applied together to obtain the required data in the required quality. Extending the current mathematical model and the corresponding algorithmic framework with regard to this aspect is a topic for further research.
- To each target, a predefined point in time is assigned that indicates when data acquisition has to start at earliest. This point in time is expressed as Earliest Time Information of Value (ETIOV).
- To each target, a predefined point in time is assigned that indicates when a data acquisition must be completed at latest. This point in time is expressed as Latest Time Information of Value (LTIOV).
- Data acquisition with regard to a target may require a certain period of time which in turn forces the asset to stay on location for that period. This period of time has to lie completely within the time interval specified by ETIOV and LTIOV.

From the operational perspective, a sensor and its carrier platform are in essence characterized as follows:

- Not all assets are equally well suited for data acquisition depending on the specific target characteristics. More precisely, only these assets that have been derived in Step One as being principally suited for a target at hand are allowed to be deployed to this specific target.
- The fleet of assets is also heterogeneous with regard to the following aspects:
  - Different restrictions regarding the maximum endurance of the assets for continuous deployment.
  - Different restrictions regarding the availability of the assets over time.
  - Different cost regarding the deployment of the assets with regard to the distance to be traveled by them and with regard to the time the assets need for traveling and for staying at the targets.
  - Different fixed costs regarding the deployment of the assets that are independent from travel distance and deployment time.
  - The assets are hosted in different home bases.
- The assets may directly transmit the data they have collected to the receiving station or store the collected data temporarily on board until they return to their home base or until they reach a geographical location where data transmission is possible. In the latter case, one has to take into account that the assets' storage capabilities are limited in practice. This aspect is currently considered in our mathematical model but it is not yet included in the algorithmic realization. Including it also there will be a topic for further research.

B. Mathematical model and algorithmic solution

As already sketched in Section III, the planning problem (corresponding to Step Two) whose operationally relevant elements have been described in the previous section has been formulated as optimization problem involving certain constrains. Thereby, basis of the mathematical problem formalization are distinct similarities between the considered planning problem and certain variants of VRPs and TOPs.

VRPs deal with the distribution of goods between depots and a set of customers via a fleet of vehicles using a certain road network. For each vehicle, the set of costumers to be served by it and the concrete traveling route have to be determined according to a specific global optimization criterion that often corresponds to the minimization of global transportation costs (expressed as costs corresponding to travel time and/or travel distance and potentially also to certain fixed costs associated with the use of the vehicles in general). Each customer demands a certain quantity of a good to be delivered and, usually, the vehicles posses capacity restrictions regarding the quantity of the good transportable by them. In the technical literature, there exist a lot of specific variants of VRPs being relevant with regard to the planning problem considered in Step Two of the two-step approach for resource-optimal sensor scheduling, for example VRPs with Time Windows, Multiple Depot VRPs, VPRs with Multiple Trips, Heterogeneous Fleet VRPs, Site-Dependent VRPs, Distance Constrained VRPs, and VRPs with Pickup and Delivery (see [11], [12], [13], [14], [15] and the references in these publications).

At TOPs, the traveling time of each vehicle is limited and visiting a certain customer delivers a certain profit. In essence, the task is to determine the individual vehicle routes such that the global profit (i.e., the sum of profits achieved by the fleet of vehicles in total) is maximal. Also with regard to this kind of routing problem, certain relevant variants exist, for example variants involving capacities and time windows (see [16], [17] and the references in these publications.). However, the set of variants of TOPs is (also from a general point of view) not as manifold as the set of variants of VRPs is.

Both, VRPs and TOPs, are of NP-hard type. This even holds for the Traveling Salesman Problem that can be seen as simplification of these two kinds of combinatorial problems. Regarding the algorithmic solution of such highly complex routing problems, today, approximate solution methods based on heuristics and meta-heuristics often are promising alternatives to exact solution methods – especially when the number of problem instances is of medium or even rather high size. Approximate solutions methods aim to determine a valid solution being of acceptable but not necessarily optimal quality (measured by the objective function that has to be optimized under constraints) within an acceptable time frame.

Our mathematical formalization of the planning problem (corresponding to Step Two) adapts the mathematical formalization of the VRP with Pickup and Delivery and with Time Windows as given in [18] by introducing problem specific elements. In a VRP with Pickup and Delivery, vehicles have not only to deliver and but also to pick-up the good at certain locations. In the ISR context, customers correspond to targets and vehicles correspond to assets. Customer demands and vehicle capacities are interpreted as quantities of data to be gathered at the targets by the assets and as the assets' storage capabilities, respectively. To model all operationally relevant problem elements, we extended the optimization problem corresponding to the VRP with Pickup and Delivery and with Time Windows by introducing additional hard constraints stating that a target whose priority exceeds a certain level must be served and that the assets' maximal endurance is not allowed to be exceeded. Also, we included an additional term in the objective function that states analogously as in TOPs that the total sum of priorities of the targets being served by assets shall become maximal.

It is interesting to note that the VRP with Pickup and Delivery and with Time Windows that been been chosen as basis of our problem formulation corresponds to a rather general VRP variant. For example, in [14], it is demonstrated how a very similar problem variant (Rich Pickup and Delivery Problem with Time Windows) can be converted into several other prominent VRP variants. Especially worth to mention with this regard is also the fact that modifying our problem formalization (corresponding to Step Two) in a formalization that does not yet include the characteristics regarding data transmission capabilities of the assets (compare last bullet in Section IV-A) is rather uncomplicated possible.

The magnitude of approximate solution methods for routing problems is designed for the solution of a specific problem variant while only certain approximate solutions methods are less fine-tuned and rather generally applicable. To solve our concrete planning problem (corresponding to Step Two), we analyzed State-of-the-Art methods with this regard and then consciously selected an algorithm possessing a rather wide application field. More precisely, a kind of Large Neighborhood Search being in essence based on an Ruin and Recreate Algorithm [19] has been selected. The practical realization is based on the Open-Source Toolkit jsprit. Current results are of good quality, however there is still potential, for example by further optimizing waiting times and by including additional adaptive elements into the heuristics/meta-heuristics. Further research will address this topic.

V. Conclusion and Further Research

A two-step approach for resource-optimal sensor scheduling constituting the basis of a computer-aided assistance system for ISR management personal has been presented. It consists of an interactive step where for each target, the set of available assets being principally suited is determined. After that, an automatic planning algorithm tries to derive concrete proposals which assets have to be finally assigned to which targets and the dedicated routes individual assets have to follow in order to serve these target. The approach has been developed in close cooperation with subject-matter experts from the ISR domain.

An important topic for further research remains evaluation covering two aspects: additional user feedback (especially when the approach is enhanced) and development of a formal evaluation framework. By the latter, additional aspects of a systematic evaluation (for example based on additional quality metrics, on benchmark-like problem instances, on comparison with ground truth values) shall be addressed.

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