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Sensor Control in NCW, Problem description and important areas

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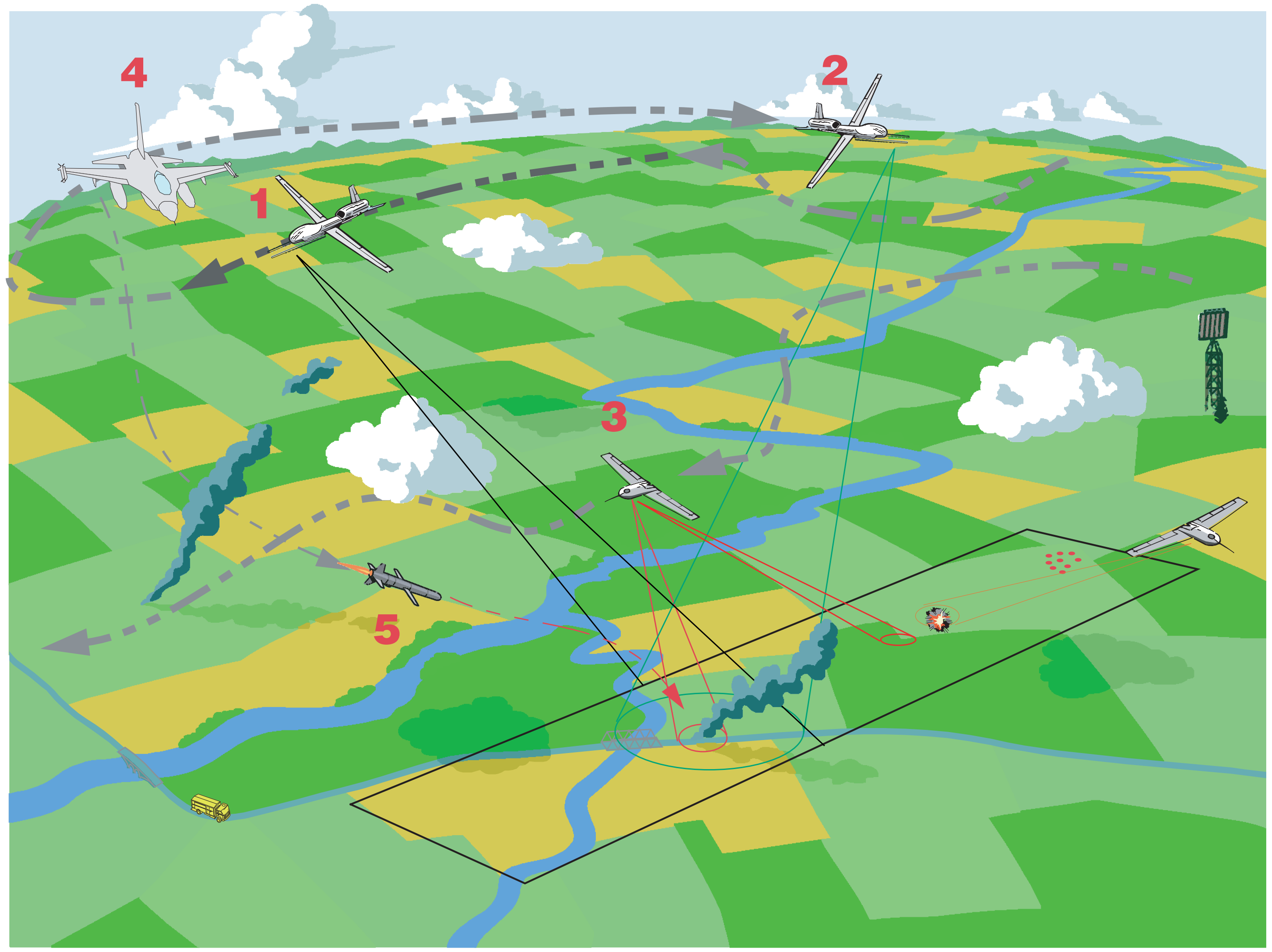

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Report title

Sensor Control in NCW,
Problem description and
important areas

Abstract (not more than 200 words)

This report gives a problem description and an overview of the area of sensor control and management of sensors connected to a communication network in a network centric warfare situation.

We describe important areas like the sensors themselves, the constraints, the character of the control goals, control decisions and the problem structure.

We have also described in more detail other topics like analysing the information need, defining management policies, resolving conflicts, distributed sensor control, planning as well as autonomous control.

We also note the problem of how to assess systems containing sensor control functionality and describes some application areas.

The sensor control problem is a very complex problem that lacks a unifying theory or model. A first attempt to some parts of a unifying theory is described/proposed in this report

Keywords

sensor control, sensor management, autonomous control, requirement conflict resolution, distributed sensor control, multi-agent systems, sensor planning

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Sammanfattning (högst 200 ord)

Den här rapporten beskriver sensorstyrproblemet och ger en översikt över området. Sensorstyrning blir viktig när sensorerna ansluts till ett kommunikationsnätverk i det kommande nätverksbaserade försvaret.

Vi pekar på viktiga delområden som sensorerna själva, olika slags begränsningar, karaktären på styrmålen, hantering av styrbeslut och strukturen på problemet.

Vi går in lite djupare på delområden såsom analys av informationsbehov, definierande av sensorstyrpolicys, lösa upp konflikter mellan olika krav, distribuering av sensorstyrfunktionalitet i nätverket och styrning i samband med autonoma farkoster.

Vi pekar vidare på problemet med att utvärdera system som innehåller sensorstyrfunktionalitet och beskriver också några applikationsområden.

Sensorstyrning är ett mycket komplext problem som saknar en enhetlig teori eller modell. Några embryon till olika delar av en sådan teori beskrivs i rapporten.

Nyckelord

sensorstyrning, sensoradministration, autonom styrning, kravkonfliktshantering , distribuerad sensorstyrning, multiagentsystem, sensorplanering

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Contents

1. Introduction and background

In a future network centric defence force there will be a great amount of sensors. The development is going towards more adaptive sensors, which dynamically can adjust to one or more situations, sometimes "simultaneously". Another line of development is to use small and cheap sensors. In different places within the network there are several operators who, at the same time, are using sensor data to solve their assignments. Sensor control concerns the processes which provide the operators with sensor data, based on their respective information demand. It is a matter of controlling who, at the moment, can decide what the sensors should do and how contradictory demands are treated, about the sensors internal work control, i.e. which operating mode should be chosen for the moment and questions of planning character, i.e. how sensors should be deployed or repositioned to get a chance to deliver the demanded information. The control problem is also concerns distributed decisions and cooperation as all operators and sensors are physically tied to different platforms.

An essential condition in order to realize the concept of network centric sensor systems is to have reliable channels for information transfer. The problem is at least twofold, i.e. one has to ensure both desired bit rate in the information transfer as well as address the question of authentication of the information. Today, there are several channels for transfer of information; fibre, telephone lines, radio, power lines, et cetera. These give together a capable net with certain redundancy. However, for military purposes, the reliability may be far from satisfactory. Also, the security may be practically absent. It can be rather easy for an external intruder to both extract information as well as plant false ditto. For these and other reasons, the question of information transfer in a network centric system seems unsolved.

Even in the case of reliable information transfer, the question of information fusion remains. It is certainly so that at a certain level, (human) operators have to collect, evaluate and control the accessible sensors and their data. However, as the number of sensors can be expected to grow, and as time may be a precious resource, there is a need for automatized information fusion. The are at least three main reasons: it is impossible for a human to perceive the amount of data produced by the sensors, it is also impossible to handle this amount of data in a rational way, and it is not possible for a human to draw sufficient conclusions on a realistic time scale. There are several ways to fuse information [9]; among the more popular ones are probabilistic methods, e.g., Bayesian network or Dempster-Shafer theory. However, it must be realized that the outcome of such a system is highly dependent on the apriori input, and it is also known that probabilistic reasoning may lead to unexpected or counter-intuitive conclusions in many circumstances. To implement a decision tool using data fusion is still a research task. On the other hand, to use the full potential of the available variety of sensors will require some kind of automatized data handling.

1.1 Requirements in NCW

In the NCW (Network Centric Warfare) environment we have many sensors which are directly connected to the network. Each sensor provides a number of services to the network. Spread out in the network, there are many information consumers in the form of automatic processes and end user operators in different roles, se figure 1.1. All consumers have a time variable need for information. The needs can vary in geographic focus, information quality, information characteristics, data update etc. Also, the consumers are not equally important to the military force at a given time interval. However, all these consumer should have the same technical possibilities but different authority. This is to maximize a flexible use of sensor resources and also give some room for individual initiative for the end user operators. There are of course many other resource types in the network that we do not discuss in this report, but there is one type that have some interest here and that is communication bandwidth and communication time delay. The communication resources could be controlled in similar ways as sensors.

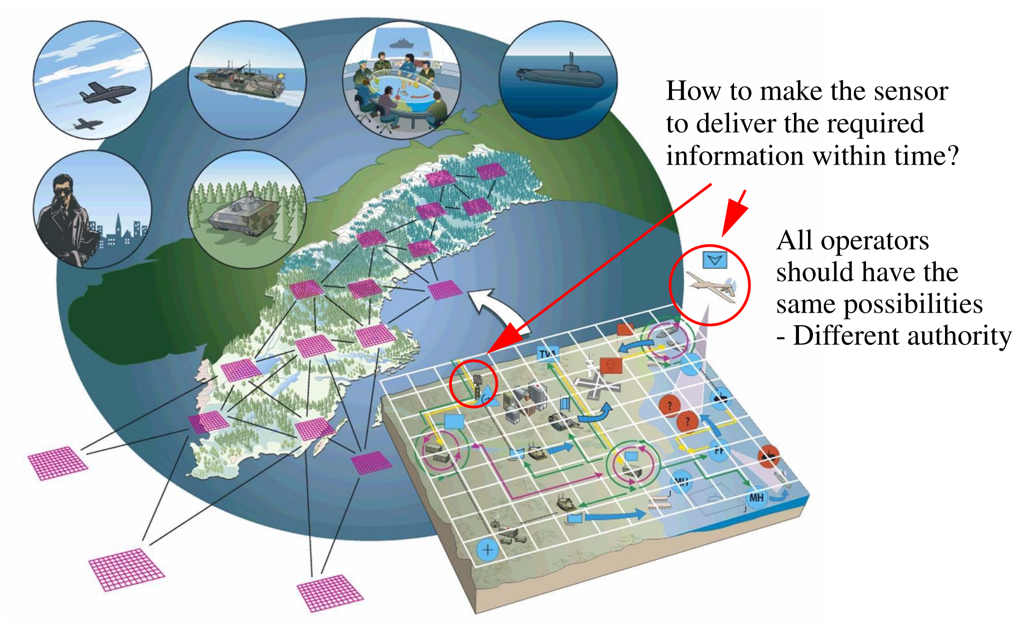


Figure 1.1: In the NCW situation there are many of sensors connected to the network. The sensor information consumers are spread around the network and should have the same possibilities.

1.2 Sensor co-operation

A great advantage with sensors working in a network environment is that many sensors can co-operate in the information gathering process. There are many reasons to do so, and we have categorized the reasons into six groups.

(i) Complementary coverage
Using several sensors to fill gaps in the coverage

(ii) Complementary sensor principles

Used to fulfil a changing information demand during a mission. An example is to first use a wide area sensor like a SAR[1] system and cue an IR[2] system to check target detections from the SAR and maybe do a classification.

(iii) Performance gain
To use several sensors to enhance the quality of the result. There are many kinds of enhancements that could be achieved:

- Better detections
- Better quality in target parameter estimates
- Higher data rate
- Higher capacity

(iv) Robustness against different kind of threats
These threats are both physical and electronical:

- Destruction
  How to avoid being a target as a consequence of a sensor operation. For example use passive modes or covert operations.
- ECM[3]
  How to reduce the effect of ECM both on each sensor and on the system. Examples are: bi- or multistatic geometry, sensor data fusion, spread spectrum, spectral diversity or distribution of located jammers and jammer parameters to the network.
- Low observable targets
  How to use many sensor to detect difficult targets. Examples are the usage of multistatic geometry or spectral diversity.

(v) New tactical behaviour
In the future it will be possible to vary the sensor tactics for example by combining sensors and arms on separate platforms or using sensors in a deceptive way.

(vi) Logistics
Using available sensors which are not the first hand choice from a performance goal perspective because they are available and could deliver the required information, possible with less quality.

In the real case there will be a certain mix of these reasons which will vary in time and in different parts of the network. In traditional command and control systems there is a scientific discipline called *data fusion*. Sometimes it is said to contain the control process as well, but we have in this description chosen to separate the control process from the fusion process. Therefore *data fusion*, in this report

- is the tool to combine data from different sources,
- have different focus depending on the actual mix of the above sensor cooperation reasons.

Traditionally, data fusion have been focused on “Performance gain” and “Complementary coverage”.

1. SAR = Synthetic Aperture Radar
2. IR = Infrared
3. ECM = Electronic Counter Measures

Sensor control on the other hand

- is the tool to achieve sensor co-operation,
- is partly a new function caused by the NCW environment,
- is previously only analysed in small sub areas of the full problem area.

1.3 "Sensor control" and other notions

In this report we have defined *sensor control* as all activities inside the network and military force C^3I-system[1] that are targeted towards all information gathering with sensors. This will involve sensor resource management on many levels as well as planning the sensor usage. Inherent in the planning process is also performance, threat and resource conflict predictions as well as scheduling and different kind of trade-off between various choices.

We have chosen to study activities that one way or another interact with the sensors and also controls them and therefore influence the sensor output. This can be regarded as a vertical slice in the C^3I-system that control the sensors. That vertical slice have we called *"sensor control"*.

Other research groups have started from the data fusion point of view and they have usually been more restrictive in the interpretation of the subject. According to that view, *sensor control* is only about controlling individual sensors while s*ensor management* is about handling several sensors and the trade-off between them. We have also seen expressions like *perception management*, [7], to handle the wider scope. The argument for this is that we are approaching the information level. *Perception management* refers to controlling the process of data acquisition from the external world to enhance percepts obtained, see figure 1.2.

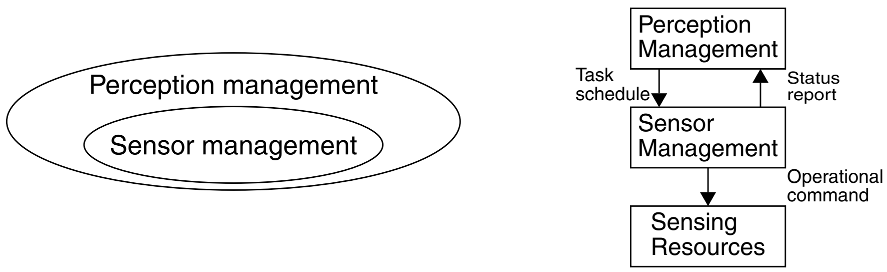


Figure 1.2: Relation between ***sensor management*** *and* ***perception management*** *according to [7].*

1.4 Prerequisites and requirements

In this section we describe prerequisites and some high level requirements on the sensor sub-systems within the C^3I-system and especially the sensor control part of the sub-system.

1. C^3I-system = Command, Control, Communication and Intelligence system

1.4.1 Prerequisites

Components

Sensors, users and network services are three type of components. A user is an operator placed somewhere in the network.

Services

The users have to their disposal a number of services in a network. Some types of services are sensor dependent. Services are typically using other services at lower levels, located at many nodes, to provide their own functionality. This will form a hierarchy of services where the lowest level services are physically located to sensor platforms.

Network adaptation

All sensors, users and services are supposed to be connected to the same communication network, e.g. all components can communicate with all other components, if required. All services and all sensors should (principally) be equally available to all users, independent on their location, as long as they have access to the network and relevant services.

Completeness

All sensors, users and network services are connected to a network with common protocols and rules.

1.4.2 General requirements

Capacity usage

All sensors should be utilized in a optimal way.

Dynamics

The sensor control functionality must be able to handle large load fluctuations without risking the global goals.

Scalability

The number of sensors, users and network services should be able to increase or decrease with minimal need for network administration or reconfiguring.

Evolution

Any component can be added, upgraded or removed from the network at any time. Users already logged in should not be affected unless they are using the component in question. New functionality should be directly usable.

Decentralizing/Vulnerability

Centralized functions in the network should be avoided. This implies that only the current users are affected when a component is upgraded, changed or deleted.

Distribution

Every component should be able to act at any physical network node.

Information quality

A user can put requirements on the technical quality of the delivered information and would also need an estimation of the actual quality delivered.

Quality is used to judge uncertainty. The ultimate goal is the answer to the questions: What do we know? What do we believe, based on what we know? What don’t we know anything about?

Commonality

All services and sensors should be controlled by a common set of rules. There should not be any special treatment of priviledged users. Important users have more authority than others, which as a side effect give them more access to services in the network.

Priority

Every user should have to his disposition some kind of currency which give him the ability to “pay” and give priority to his sensor usage orders. This “payment” give the right to use the sensor resources. How this specialized currency should be distributed among the users are up to the military authorities to decide.

Need for education Every user should understand how the sensor control is working and how the priorities are established. It should also be possible to practice sensor control functionality under safe conditions.

Availability The sensor system should be available for its intended use when it is really needed e.g. in crisis and war-like situations.

Security The sensor system has additional security problems to handle compared to the underlying communication network. Examples of security problems are: unauthorized use, overload caused by the opposition and false target reports injected by the opposition. These problems should be minimized.

2. Sensor control

To the front end user, the sensor resources may be very different from the sensor hardware characteristics. For an user, it is natural to think in terms of sensor modes, e.g., surveillance, tracking, target recognition. For the specific sensor, it may be more natural to consider pulse repetition frequency (PRF), bandwidth, power consumption or other similar features. Therefore, sensor resources can be classified in several ways, for instance according to their capability (detection, classification, recognition) or through their general type (IR, laser, radar, acoustic sensor). Thus, the concept of sensor control varies with the perspective.

One of the tasks for a sensor control system is therefore to be able to translate operator needs into sensor requirements, i.e., not only do we have the problem of fusing information from the sensors, we must also ask the relevant questions so that the sensor control system can design a measurement, schedule it in time, perform the measurement, analyse the result and update our abstract representation of the real world. In addition. This must be done by using the sensor resources that deliver the requested information at minimal cost. As can be imagined, that is not an easy task.

Common for all type of control is that the overall control goal must be clearly defined as well as the constraints and additional requirements. Also it is our belief that it is not the mean performance figures that will win a battle, it is the extreme ones, good or bad, well used against the opposition.

The sensor control function can be seen as several layers which have different time-scales. Control with short time-scale concerns choosing a sensor mode and the associated parameters to the selected sensor mode. Control with medium time-scale mainly concerns resource allocation and path-planning. Control with long time-scale concerns deciding where sensor platforms should operate as well as when and where they should be relocated. The resource allocation problem is a universal problem that exist in many forms within the C^3I-system.

The control function contains the selection of sensors and sensor platforms to be used in a certain situation. The choice depends on factors like weather, environment, expected information need, systems available to the opposition and our own dispositions. Costs and the risks to losses are other factors to consider as well as the uncertainties in all estimates.

Traditionally every sensor is allocated to a specific military unit and that unit has total control over the sensor. Cooperative uses have always been performed by the “owning” units premises. This will not work in a future where all sensors sare available for cooperative use. The traditional way will lead to: usage permits are handled to slowly, in too big time intervals and too randomly to let a resource be regarded as valuable by a certain commander. The resource owner also tends to have a hard grip on “his” resource as he does not dare to let it out in fear of not been able to use his own resource when needed. The management of resource usage (the resource allocation) needs to be formalized and given a technical support system.

To support the control medium and long time-scale planning there is a need for a number of planning tools to estimate performance, analyse risks, predict event chains etc. These tools need to be adapted to the actual role of a user.

2.1 Controllable resources/Resources to control

In this section, we consider general aspects on sensors and in which aspects they can be controlled. Details on particular sensors are found elsewhere. An overview of sensors is given in [10], visual and IR sensors are described in [12], acoustics in [11], radar sensors in [14], electronic support measures (ESM) in [15] and laser radar [13], [16]. Visual, IR, radar, ESM and laser sensors detect electromagnetic waves while acoustic sensors detect mechanical waves, see Figure 2.1-2.3. Firstly the fundamental, physical properties of sensors are described, secondly, some typical operation modes of a sensor system are described and finally, the possibilities to control the sensor systems are discussed.

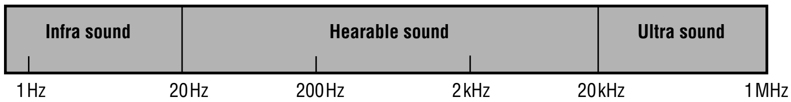


Figure 2.1: Mechanic waves spectrum. Wavelengths axis indicates the operational area for infrasound, speech, ultra sound.

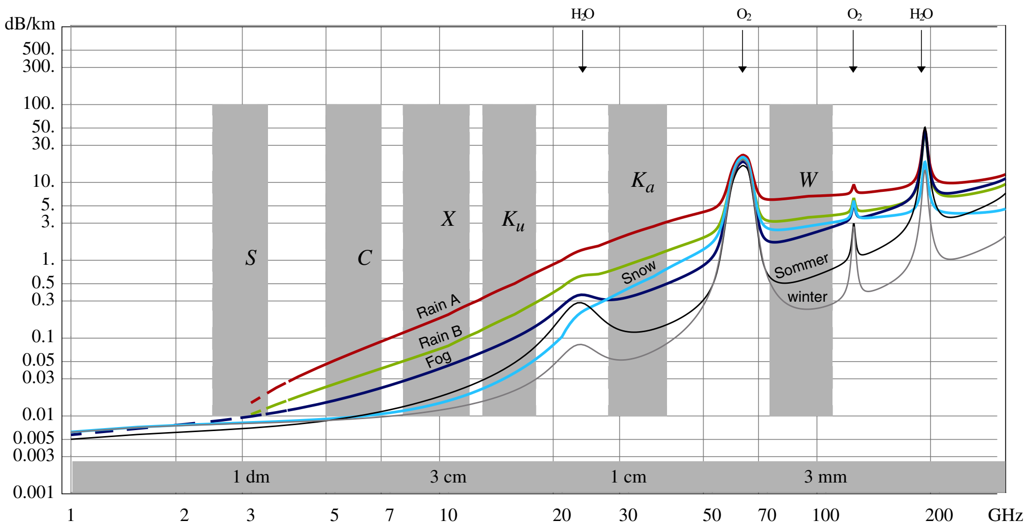


Figure 2.2: Attenuation in the microwave region of the electromagnetic spectrum under different conditions and typical values during summer and winter seasons. The attenuation peaks are caused by the different gases in the atmosphere like O_2 and H_2O.

2.1.1 General sensor phenomenology

A fundamental difference between sensors is if they are passive sensors, which contain a detector but not a transmitter, or active sensors, that contain both a detector and transmitter. Both passive and active sensors register target phenomena that are used in the detector and in the signal/image processing to estimate features of the target. Active sensors also have the possibility to measure the target's range, velocity and vibrations (for short wavelengths). Active sensors, which transmit signals, are easier to detect,

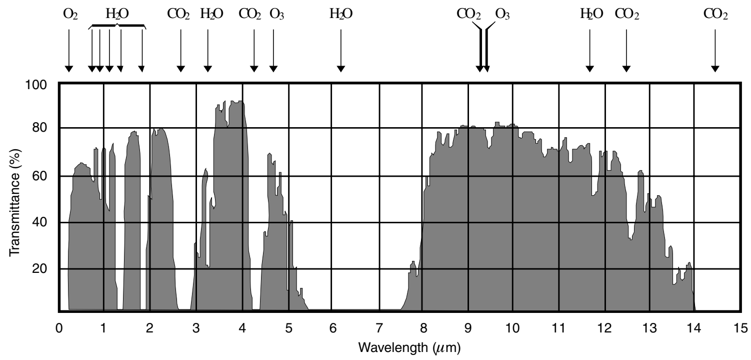


Figure 2.3: Transmittance in the optical region of the electromagnetic spectrum at a distance of 2 km. Wavelengths axis indicates the operational area for IR, laser, and the visual spectrum. The figure also indicate the gases that cause the attenuation.

but on the other hand the range information is given explicitly. It is also possible to make an active sensor harder to detect by limiting the transmission in azimuth or by modulation of the transmitted signal. A passive sensor is usually hard to detect but the range resolution is generally low. Typical passive sensors are visual, IR (infrared), ESM and some types of acoustic sensors. Typical active sensors are radar, ladar (laser) and sonar (active acoustic). See figure 2.5 for a schematic sensor. It is also possible to combine active and passive sensors, for example a laser radar together with an IR detector.

Another fundamental characteristic of a sensor is caused by the operating wavelength. Generally, a short wavelength gives detailed information of the sensed target, but a short wavelength is more sensitive to atmospheric attenuation (due to rain, fog, dust etc.). A longer wavelength, on the other hand is less sensitive to atmospheric attenuation, but the length of the wavelength limits the possibility to resolve the sensed target. Longer wavelengths have larger problems with wave propagation like refraction and interference. Sensors operating with a large wavelength need physically large transmitters and detectors. New types of sensors have the possibility to resolve the detected wavelengths into sub-bands, so-called broadband (RF), multi- or hyperspectral (optical) sensors, to increase the resolution of the target. Further there are sensors where the detector elements can be tunable.

The angular resolution is limited by the sensors aperture size, angular spread of the transmitted signal, the detector's field of view and, in the case of a sensor array, the number of detecting elements (in the detector). An array of detecting elements has better angular resolution than a single element and a matrix of elements has better angular resolution than an array.

High resolution sensors create large amounts of data. This puts high demands on computation capacity and on the network. If data is processed on the sensor platform, the platform needs computation capacity and memory, but there is less demands on the network's communication bandwidth. If data are first delivered over the network to a processing unit, the network needs to have large bandwidth. Data and image compression are usually needed in both cases.

The fundamental limits described above results in the conclusion that for many applications, one sensor is not enough to achieve robust operation.

Therefore, systems with several sensors are attractive. Two typical system types are identified: arrays/networks of identical sensors, hereafter called sensor arrays/networks, and systems containing different sensor types on the same platform, hereafter called multi sensor systems. Sensor arrays are often used to increase the range and position estimates. Multi sensor systems are typically used to combine passive/active behaviour and long detection ranges with high range/angular resolution. For both sensor arrays and multi sensor systems the systems are more complex compared to single sensor systems; the benefit is better performance.

2.1.2 Sensor hardware

The sensor control function was first actualized by the invention of the multifunction radar based on an array antenna, se figure 2.4. In the future we will see much more flexible IR-systems and also truly multifunction laser-sensors with capabilities for communication as well as for electronic countermeasures.

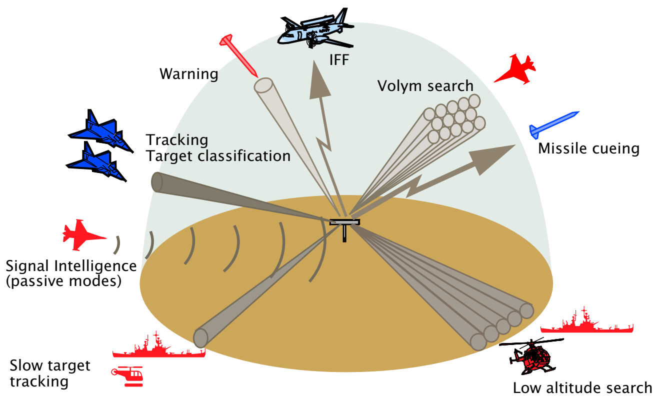


Figure 2.4: A multifunction radar with many time-shared modes. This radar type is based on an Active Electronically Steered Array antenna (AESA). There are many motives for this type of radar apart from the flexibility we try to address in this report.

In figure 2.5 we show a schematic diagram for a generic sensor without a platform. This diagram shows that many subsystems are affected by the control. It also shows that there could be one to many separate channels, both in the receiver and transmitter (if an active sensor) side of the sensor. These channels work together to form a common result after some form of signal processing like detection, feature extraction or other wanted estimates. In a simple optical case there is only one receiving channel behind a mechanical scanned lens system. The other contrast is the multifunction radar based on a digital array antenna, both in the receiver and transmittter side, where we have the full freedom to do relevant signal processing if the processing power is high enough. An even more general idea is the "common RF-front-end" which tries to do every RF-based function in one system. In that case we have an array with channels of different type, dealing with different centre frequencies and channel bandwidths, but also truly parallel operations e.g. one part of the antenna does communication while another part acts as a radar warner and a third part acts as a radar. Electronical scanning with an array sensor have also been demonstrated in the optical field with phase-shifting devices and lasers.

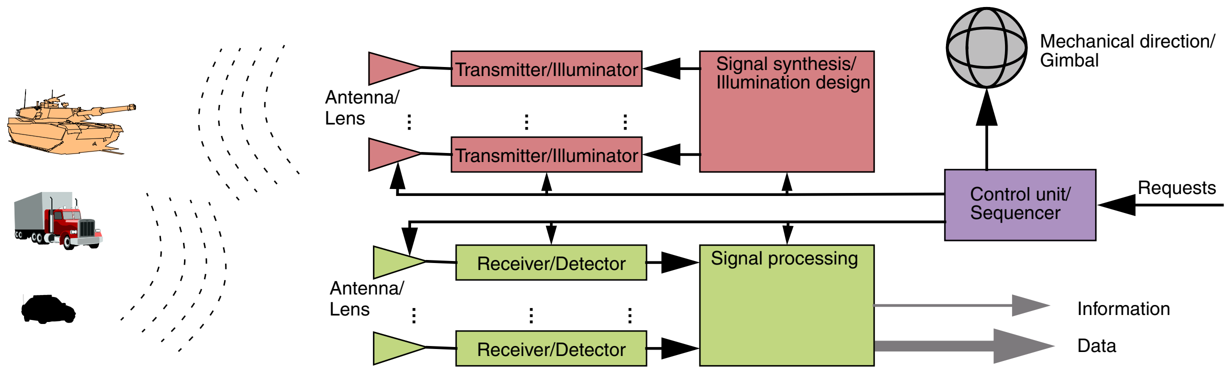


Figure 2.5: Schematic sensor hardware. Some sensors have an array of channels, both on the illuminating and on the receiving side, while other only has one channel and/or lack the active side. Some sensors are mounted on turn tables or gimbals to centre the field of view in any direction, regardless of platform pointing vector.

2.1.3 Sensor mode of operation

Many modern sensors are adaptive in their behaviour. The adaptation is constructed in different ways, for instance: hardware parameters, transmitted waveform and/or in the signal processing. Taking all this adaptation possibilities into account there will simply be too many parameters. A more constructive way is to group the parameter settings into groups which describe the purpose of the sensor measurement and assign to those groups a new set of more abstract parameters which further refine the measurement. This *mode of operation* is an abstract way of describing how to choose hardware, software, transmitting and signal processing parameters to achieve a certain measurement purpose. These nodes are independent of the type of sensor but of course some modes are more relevant than others for a given type of sensor.

The sensor modes typically change very rapidly from time to time. In many sensors the modes of operation are mutually exclusive, but there will of course be exceptions when we can have parallel modes. There are also tasks where several operation modes are applied. For example, weapon delivery is a combination of detection, tracking, classification, recognition for both finding the target and damage verification. In identification and fingerprinting, target characterization and tracking are combined with high level intelligence processing. In the same way, missile warning and mapping tasks contains combinations of the operation modes listed below.

Search

This mode has the purpose of detecting new targets or interesting objects in a certain search volume or area. The result is new objects with various confidence. Associated attributes could also be reported like position, direction, strength, shape etc. There will be cases where the result will be a report indicating a possibly large volume containing a target, sometimes associated with a signature. The duration of a search mode varies with the search volume and the confirmation level.

Track The tracking mode has the purpose of updating or following an already known target to keep track of its position, direction and behaviour over time. The duration is typically short with a relatively high update rate for fast and manoeuvring targets. Slow or non manoeuvring targets do not need a high update rate. There also exists an optimal time when a track update have to be performed.

Classification/ Recognition/ Identification These modes has the purpose of classifying an already known and tracked target to its type and ultimately finding its identity. This is typically a sequence of measurements, possibly lengthy, to extract a number of features from the target. This sequence of measurements is in some cases uninterruptable while in other cases it could be regarded as a sequential test which could be aborted when enough confidence have been gained.

Classification, This mode has the purpose of classifying a detected and tracked target to its target class (building, vehicle etc.). A number of target features are estimated, like size, shape and texture.

Recognition, In the recognition mode, the target subclass is determined. For example, a tracked and classified vehicle is recognized as a tank or a truck. Model library matching is common.

Identification, In the identification mode, the model/make of the target is resolved, for example a tank is identified as an M60 or a T72.

Characterization, In this mode detailed physical characteristics of the target are determined, e.g., a fighter plane is characterized as a MIG-29 with air-to-air missile.

IFF (Identifying Friend or Foe) The purpose of the IFF is to verify that a target belongs to our own forces, i.e. the target is requested to show some sign of its identity. That return is to be compared against a set of allowed returns. The duration of this mode is usually short.

Weapon delivery This mode could be further broken down into sub-modes: Firstly a local search to verify the target's position. If not try to find it nearby. Secondly a illumination of the target to be used by a bistatic seeker in a missile or a high rate track update of both the target and the missile. Thirdly a verification of a hit or a miss. These modes has typically very high priority under a short period of time. Delays are generally not acceptable.

Navigation This mode is used to verify our own platform's position with some kind of a map and with the planned position or path. Typically a short duration mode.

Communication This mode is for using an active RF-based or laser-based sensor for communication with another platform. A high-gain antenna beam or a laser beam is pointed to the other part and messages are exchanged. It is also possible to listen only to incoming messages in a passive situation. The duration could be lengthy.

Jamming The purpose of this mode is to actively jam one or more sensors located on the opponents platforms. The waveforms are chosen to damage or fool the opponent sensor systems.

Missile warning This is a high priority mode with the purpose of detecting launched and/or approaching missiles.

Active signature control

There are potential possibilities to actively modify the platform signature in a specific direction by sending out a signal complementary to the opponent's waveform. This signal causes the platform signature to be modified and hopefully reduced. The priority of this mode is very high.

Mapping

This is not one mode. It is several modes with the purpose of making some kind of a map of the background. It could be maps over the terrain with roads, buildings, power lines etc. but also short duration maps over the weather or certain aspects of it for example visibility. These modes are usually lengthy in time.

Signal intelligence

The purpose of this mode is to detect new signals or new signal behaviour to be used later in tactical signal intelligence equipment.

Bistatic and multistatic operation

Many of the above modes may also be used in monostatic, bistatic or multistatic configurations. Monostatic means that only one sensor is involved. Bistatic means that two sensors are required and both need to function properly. This means a higher complexity but also better performance. Multistatic operation involves more than two sensors and are therefore even more complex and even better performance can be gained.

2.1.4 Control of sensors

The sensor control can be grouped into three classes, control of the single sensor, control of the multi sensor system and the (multi) sensor platform.

For a single sensor, see the schematic in figure 2.5, there is a number of sub units that can be controlled. When operating in an active mode, the transmitted signal firstly have to be synthesised e.g. the modulating signal's shape have to be decided and generated. Secondly the wavelength of the carrier signal have to be selected by tuning the oscillator or laser and relevant part of the antenna or lens. Thirdly, the power volume distribution have to be decided and effectuated by adjusting the mechanical alignment or by commanding a lens or antenna sub-system. On the receiving side there are also a lot of parameters to select, like the sensitivity distribution, by adjusting the mechanical alignment or by commanding a lens or antenna sub-system. Also, other parameters have to be matched with the transmitted signal e.g. carrier frequency, bandwidth and signal processing chain.

If the sensor is of a purely passive type, then the active side in figure 2.5, is of course non-existing and if the sensor is a multifunction sensor and is operating in a passive mode, then the transmitter is switched off. A multifunction sensor could of course operate in a purely active mode as is required when it is used as a jammer or as a illuminator for other sensors in bi- or multistatic modes.

For a multi sensor system, the interaction of the sensors can be controlled. For example, the usage over time can vary between serial and parallel measurements and processing mode depending on the task. Also, the relative positions of individual sensors can be important in order to achieve certain functions. An example of this is bistatic SAR where the transmitter must illuminate the scene from a specific sector while the receiving platform is moving in a path close to the target area.

The sensor systems are mounted on some kind of a manned or unmanned platform. The sensors can be placed on airborne vehicles (aeroplanes, helicopters, aerostats), in space satellites, on ships above or below the water surface, or on ground vehicles. Further, the sensors can be placed stationary on ground or just beneath the ground surface or in some kind of elevated platform. These mounting platforms can all be controlled in certain ways. The obvious way is the 4-dimensional path (time included). It may also be possible to control when a simple sensor is enabled or deployed in the operation area or the elevation level of a static platform.

2.2 Constraints

The sensor control can be seen as a large and complex optimization problem with many constraints which limit the set of choices or parameters. We have divided those constraints into two groups: soft and hard, based on the nature of the constraint.

2.2.1 Soft constraints

A soft constraint describes things or relations that can be violated to a certain degree. The degree of usefulness is a normalized number between 0 and 1. This number tells us how much of the intended function we will get. An example of a soft constraint is the time interval when the sensor system is allowed to do a track update of an already tracked target. It is not useful to do such an update too early, but the uncertainty area where we expect to find the target will increase if we wait too long. Another example of soft constraint is the allowed wavelength to use. Yet another example is the bistatic angle in bistatic modes that describes the quality of a measurement.

2.2.2 Hard constraints

A hard constraint cannot be violated. If this type of constraint is violated, we will not achieve the intended function. There are many examples of hard constraints. Examples are:

- The target have to be in the field of view.
- The available power have to be enough for the intended function.
- The target have to be in unambiguous range-doppler cells and not in the blind area, see figure 2.6.

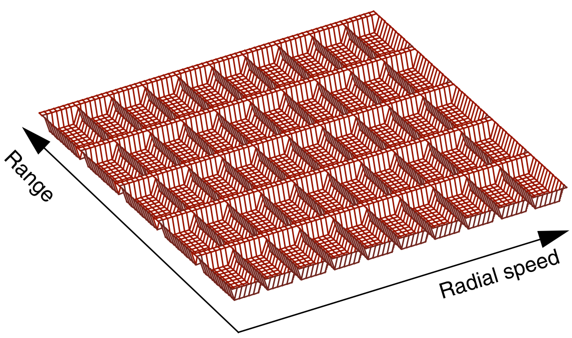


Figure 2.6: Ambiguity in range and range rate caused by the pulse repetition frequency in a pulsed sensor. Targets in different ambiguous range and doppler cells all look as they are located in the first lower left one.

2.3 Control goals

Obviously, there are no universal control goals. In some circumstances, the only objective may be surveillance and information retrieval. In some other situations the sensor control may be aimed at a highly specific task. Also, the authority of the operators may vary. However, regardless of the type of mission, common control goals are parameters like reliability, clearness and consistency. These goals are somewhat contradictory, as clear and easy-to-understand data are in danger of oversimplifying the information. A human operator may only be capable of assimilate simple statements like "target" or "no target", while a control system may have a more complex and detailed view. This means that apart from clever decision mechanisms, there is the separate issue of *presentation* of data.

In the network environment there are many goals. All operators have their own goals which vary from time to time. We also have goals at higher levels like "do not waste resources", "operate as covert as possible" or "minimize physical threats". The total combination of goals is therefore very complex and multidimensional. The only practical way of handling this is to partition the problem intelligently and optimize each part separately. The complex goal function is the basis that will form some kind of a decision variable.

On the higher planning levels there is a need to predict the outcome of decision alternatives in order to choose the best one. The objective is then to investigate the different parts of the goal function and to find a sequence of choices that satisfy our requirements and is as optimal as possible. Satisfying our requirements means that all constraints are fulfilled. The optimum is defined by the goal function which weights other, smaller in scope, functions together, like the probability of detection, probability for false alarm, see equation (2-1) below, based on the users requests and the current state of the system.

$$
\begin{aligned}
&P_{\text{detection}}(\text{range, view angle, environment, time, } \ldots) \\
&P_{\text{False Alarm}}(\text{range, view angle, environment, time, } \ldots) \\
&P_{c\text{lassificcation}}(\text{range, view angle, environment, time, } \ldots) \\
&P_{\text{positionng}}(\text{range, view angle, environment, time, } \ldots) \\
&P_{\text{Not successful}}(\text{threat, environment, time} \ldots) \\
&\ldots
\end{aligned}
\tag{2-1}
$$

These functions will predict in advance a typical behaviour of a sensor or a sensor system. When it comes to combining these figures it is like comparing apples and pears. It depends on the actual situation and preferences what to choose. In practice it is also quite difficult to find those functions in a trustworthy manner for all sensor types and possible conditions that influence the result.

It can be noted that it is necessary to estimate the background for each sensor in order to find good predictions. It is also necessary to estimate the opponents reaction if he finds out that he is under surveillance. In both cases, this is best done by using model-based estimation.

2.4 Control strategies

We have to consider many kind of strategies. First of all we have the strategies coupled to individual sensor types, for example an adaptive multifunction radar. It has the ability to steer the transmitted power and the receiving sensitivity in different directions, it is also possible to steer the aperture. Therefore, there are beam steering strategies for this type of sensor. For other sensor types we can find similar specialized strategies. On higher levels there are also strategies, for example how to select the correct sensor in a specific situation.

Those strategies can be formalized and grouped to form what we are calling a “Sensor Management Policy” (SMP). This policy describes how prioritizing should be done between a large number of choices. It also prescribes some additional constraints. This policy can be changed individually in each platform, or distributed, chosen and updated centrally from one node in the network. The latter is perhaps more suitable if the platform is autonomous. It is easier for an operator to understand and choose between policies than it is to choose the individual strategies on several topics.

2.5 Control decisions

In this kind of control system there are a lot of decisions to be made. As a matter of fact most of the control system is about discrete decisions. The part of the system that includes traditional dynamical models which include for instance the navigational system of an unmanned platform is out of the scope of this report. What we are trying to do is to *command* those platforms to effectively use the on-board sensors.

Control decisions are made in the planning process on all levels. They are made to fulfil some kind of multidimensional goals, see section 2.3.

The overall control strategy is largely dependent on the system in question. Important factors are the systems complexity and heterogeneity. Other important factors are time aspects, e.g. how long the system can wait before a response is required, or if human intervention is allowed or not. Furthermore, in some cases a sensor system is required to choose between a couple of well defined alternatives, while in some cases it is asked to make complicated decisions. Also, the cost of making the wrong decision as well as the need to communicate with other systems has to be taken into account.

2.5.1 Methods

There are several ways to describe different strategies. In addition, a given strategy can be described and annotated in different ways in different applications areas. Nevertheless, there are some basic principles underlying different control methods. However, it must be noted that the validity of these methods does not only lie in their principles, but equally much in the modelling of the environment in which the sensor system is supposed to act. This means that it is dangerous to say that some methods are generally better than others, although some may have wider generality. If the environment is poorly modelled, most methods will fail.

The methods can be characterized in several ways. For instance, depending on time aspects and the overall situation, the methods may or may not involve feedback which can be used for further reasoning. Perhaps the most obvious situation where feedback is fundamental is missile guidance, where the missile is supposed to track and search a hostile object. If both the target and the missile are observable, the missile guidance is updated through observations. Other situations where feedback is used, and where the temporal aspect is still valid, but less prominent, is for instance the use of probabilistic networks. In such networks, it is sometimes rather the basic assumptions that are adjusted according to observations, and this will in turn affect the conclusions. In still other situations, feedback is of no use. This is the case when one have the choice between "act" or "not act", and where later information merely tells if the decision was right or wrong. With these remarks in mind, we list a few methods for control decisions. For a more complete account, we refer to [1].

Among the methods we can discriminate several types or strategies. For instance, there are conventional if-then-else programming, knowledge based methods, and utility function methods. Se also appendix C on sensor management.

- Conventional if-then-else programming. This is a strictly rule based technology, where the program is supposed to cover all possible cases explicitly. Except for small and simple systems, these programs becomes very large and are therefore hard to survey and maintain. Also minor changes in the conditions may be hard to implement.
- Knowledge based methods are for example:
    - Fuzzy reasoning. This is still a rule based method, but with the interesting feature that it can describe quantities which are hard to quantize in a systematic way. This means that properties as "moves fast" or "rather few objects" etc. can be modeled.
    - Bayesian network or probabilistic network. These networks also attempts to handle uncertainties. The underlying principle is extensive use of Bayes' rule, sometimes together with the distinction between probability and plausibility, where the latter indicates a subjective opinion rather than frequency based interpretation of the probabilities. Evidence of outcomes are fed into the system, which gives a kind of feedback. For applications to operations analysis, see for instance [2].
- Utility function methods are based on the formation of a utility function U which in principle depends on all variables affecting the situation in question. Each realization of such an utility function is based on some kind of modelling which has to balance the requirements of capability of correctly describing the system as well as being mathematically manageable. The operations are chosen so as at maximize the utility function. An example is traditional Kalman filtering. In its simplest form, the Kalman filter assumes a linear Gaussian finite dimensional world, where an expected error is minimized.

  Characteristics of utility methods are:
    - Mathematically attractive
    - Hard to predict the effect of a small change in the utility function

❏ Multi time scale is hard to achieve

We conclude this section with the remark that concepts like “data fusion”, “operations research”, “artificial intelligence” and similar have not been regarded as methods, but rather as research fields.

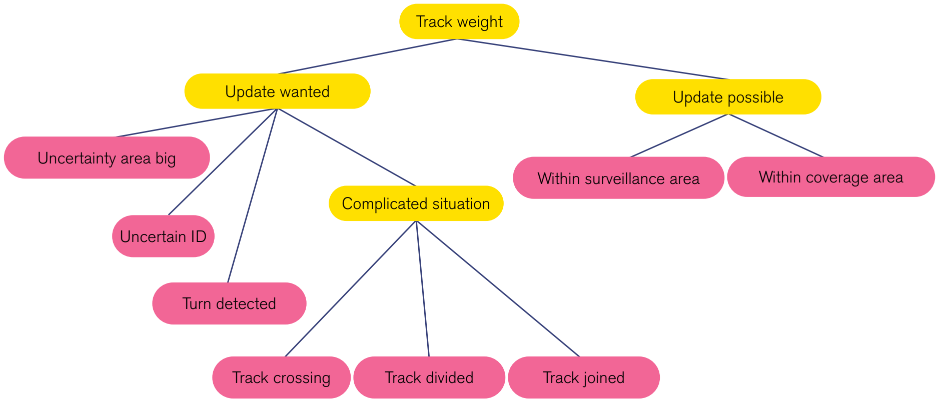


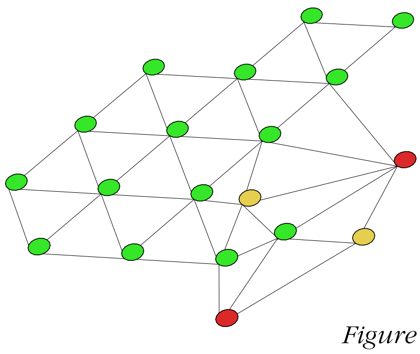
Figure 2.7: An example of a decision tree based on fuzzy reasoning. In each node there is an estimate of the belief of the statement described by the node.

2.6 Problem structure

As have been described previously, this is a very complex problem with no simple solutions. In this section we describe some of the structural properties we have to face.

First of all, we could describe the control problem as hierarchical within the C^3I-system with the supreme commander at the highest level and the hardware sensor resources at the lowest level, see figure 2.8. These levels define a command and control influenced hierarchy.

Secondly, there exist many control loops inside this system. Many of them can be considered completely contained in one level but there are also many control loops that crosses one or several level boundaries. It can be shown that the feedback in those loops are necessary to form a stable and closed system. Also the time delay of the feedback information is important for a stable system.



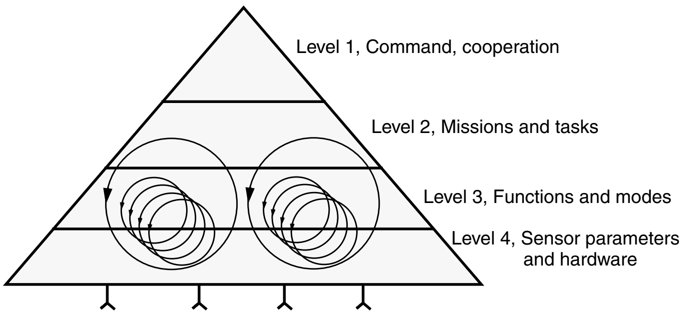


Figure 2.8: Right: There are several decision and control loops that crosses level boundaries. Also, left, functionality is distributed over nodes in the network. Conflicts are handled by “negotiation” between agents and processes.

A third aspect is the network and how functionality is subdivided and distributed over the nodes. This have a direct influence on time delays and reachability between functions which indirectly influence system reliability, and the systems thrustworthyness. A fourth aspect is the communication protocols that define the rules for exchanging information between nodes.

We can further refine the structure description by looking more into the sensor platform and investigate the internal structure. A sensor system on a sensor platform, as can be seen in figure 2.9, consists of the sensor itself and a control system. The control system builds up an dynamical database of objects that describe the important aspect of the outside world as viewed by this platform. The system also uses more static data as an help in the process. The control system gives measurement orders to the sensor and the signal processing after deciding the most important action. Output is the data from the signal processing that is used to update the symbolic representation of outside world and/or is distributed to the end user somewhere in the network. In this scheme it is the control system that decides what to do and therefore operates the system, not the actual sensor. If the sensor is a conventional radar with a mechanical scanning antenna, then the control system decides start, stop, pulse frequencies and similar parameters. The control system can therefore be simplified compared to the fully adaptable sensor.

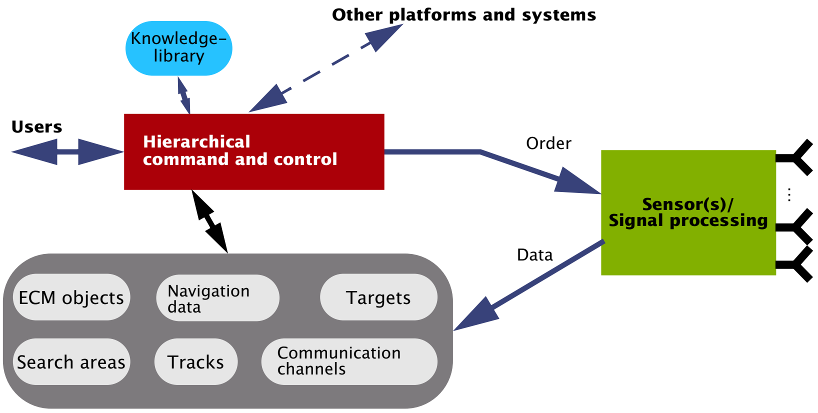


Figure 2.9: A sensor system consists not only of the sensor itself, there is also a control system and a large amount of static and dynamic data.

On a platform with several different sensors on-board this structure will typically be slightly modified. In addition, we have an internal hierarchy of sensor controllers where we have one micro sensor controller for each sensor and one macro controller that controls the micro controllers and handles aspects which are common to all sensors, see figure 2.10

An important reason for this kind of structuring is to subdivide the system into smaller more manageable modules and in that way tackle the complexity and make the system easier to implement.

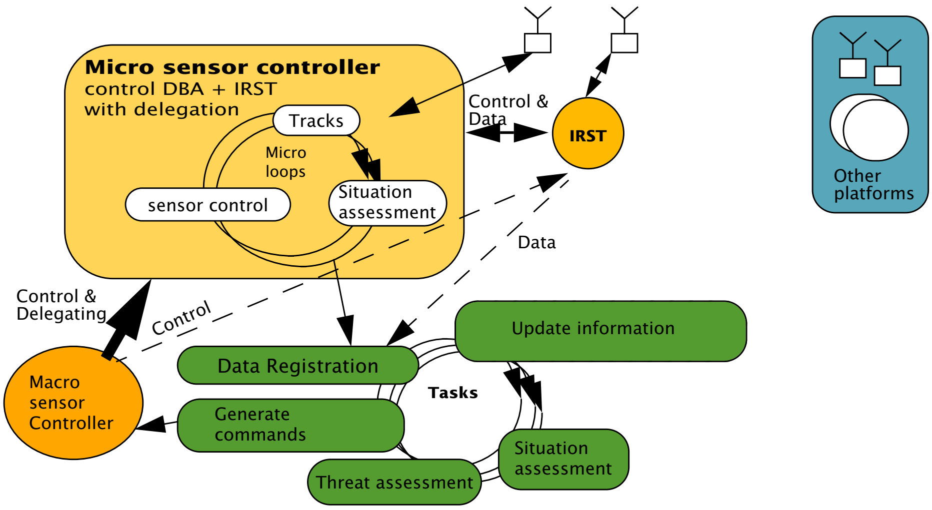


Figure 2.10:Different control loops in coordination between micro- and macro sensor controllers

3. Analysis of sensor control functions

3.1 Analysis of information needs

It is necessary to have some kind of a model of how a typical mission looks like when it comes to the information needs. One such model was invented during a study led by the military authorities with our participation, see figure 3.1. This model identifies that every mission can be divided into the following phases:

(i) Surveillance. In this phase it is important to detect if something unusual is happening. In other words detecting differences from the "normal picture".

(ii) "Act"/"No act". In this phase it is decided whether the detected difference is something we should worry about, i.e. If we should act or not.

(iii) Choice of mission and military unit. In this phase we decide what to do and which unit should be responsible for the decided action.

(iv) Mission. This phase is about execution of the decided action.

(v) Assessment. In the last phase we need to know whether the executed action was successful or not.

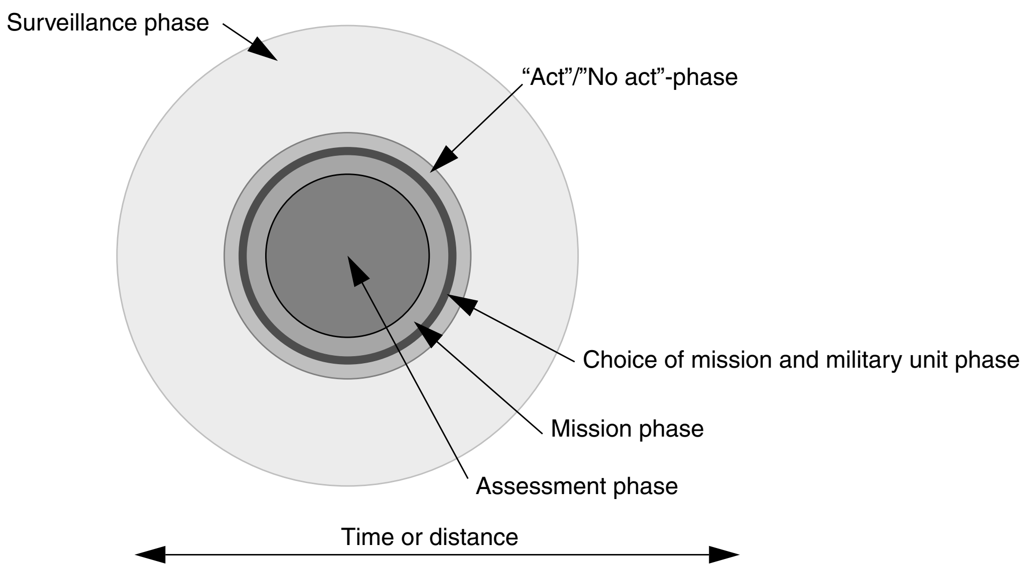


Figure 3.1: A simple model to serve as a guide in the process of finding the information requirements .

The information needs are different in all these phases. There are differences both in the type of information as well as the parameter values on the requirements. Example of parameters are resolution, probability of detection, false alarm rate or probability of identification.

A model of this type is suitable to define the correct requirements both in planning with long and medium time-scale. This kind of model can also be suitable when trying to analyse or do assessment of complete sensor systems as described in section 4.

3.2 Methods for control strategies

As was described in section 2.1.3, a sensor mode is a predetermined interplay of parameters, generated in order to avoid complex and detailed searching and tuning of parameter values each time a new sensor task is selected for operation. For many complex sensor systems, there is no predefined model that can supply feasible values to all the parameters needed to be set (for immediate operation), and no other practical search methods (such as trial-and-error) may be available. One solution is to define, shape and store a set of modes, each one generated to suit a certain tactical situation or goal. Usually, each mode is a value assignment of all adjustable sensor parameters. The operative choice of a sensor mode is then easy to hand over to an operator, or to include in a set of automatic actions to perform in a predefined situation. A sensor mode is almost exclusively defined to be the interplay of the parameters of a single sensor.

Just as a sensor mode is a predetermined interplay of sensor parameters, a sensor management policy (SMP) is a predetermined interplay of sensor modes. A policy describes the interplay of multiple sensors. The effect is, analogously to the sensor modes, that it replaces the setting of a multitude of parameters on a detailed and technical level with an operation selection on a more abstract level.

Contents for SMP

A policy consists of three basic components: operating scheme, performance standard and adaptation procedure, see [8]. The operating scheme includes guidance about what actions the different sensors in the sensor suite perform in different target situations and the goal performance for each of them. The performance standard specifies performance set points, which may be expressed for example in terms of quality requirements or figures of merits such as range for 90% detection probability for some kind of object. The adaptation procedure is a description of what sensor actions to take, if the required performance standard is unavailable without sensor overloading.

Forms for SMP

No established form exists today for SMP:s, but [8] recommends fuzzy rules. For a busy user, such as the operator of a fighter, the SMP capacity must be presented in a simple way. Probably, SMP selection is then an action performed in a similar way as mode selection in a single sensor system, by pushing a button, or pointing a cursor in a display menu. In such environments, all selectable SMP:s are predefined. For operators with more time, it may be desirable to have a support tool with which SMP:s can be adjusted or fabricated. Capacity to do SMP adjustments is important in cases where it is impossible to know in advance the exact set of available sensors. SMP selection may also be done automatically as a result of a changing situation.

3.2.1 An example of sensor management policies

This example is *multiple target tracking with an agile beam radar*. The flexibility of this sensor type gives it a flavour of multiple sensor management. In complex measurement situations, different modes are applied sequentially or simultaneously to the different targets and areas in order to maintain the tracks with acceptable quality, often with the goal to use as little as possible of the total sensor resources.

- Track initiation policies. These policies allocate - as a response to a search hit - enough sensor resources to quickly generate and stabilize a new track. This avoids early track instability and loss.
- Manoeuvre adaptation policies. These policies use information estimated by advanced manoeuvre detection algorithms (for example IMM[1]) to allocate resources that avoid track instability during sudden manoeuvres. The fine angular accuracy of IR devices allow them to play an important role in such policies.
- Countermeasure adaptation policies. These policies use sensor resources and modes that are useful when tracking is disrupted by electronic countermeasures.
- Emission control policies. Policies which limit the use of active sensors. These policies turn to low probability of intercept tracking modes.

3.2.2 Generalization of the SMP concept

The SMP concept could be generalized for the higher level control. This means that there are some policies to control preferred behaviour. The advantage is that the operator can do the control action at an higher abstraction level, which minimize the work load. The disadvantage can be that it will be more difficult to finetune the behaviour. The policy concept is also suitable for controlling the high level behaviour of conflict resolution methods as described in section 3.3.

3.3 Resolving conflicting requirements

Conflicts between different requirements can arise at all hieratically levels. The ultimate conflict resolver is the operators, but they have very limited capacity and can not handle so many conflicts per time unit. The operators also have problems if the conflict situation is very large, complex or a decision need to be done very fast.

Conflict management at resource sharing

Sensor units may be shared among several users, most often over the time. This usually requires manual negotiations each time, at least for hardware resources. If a hardware resource unit is wanted by more than one user at the same time, there is a conflict and a conflict resolution mechanism is necessary. An alternative to manual intervention is an automatic conflict resolution system. Manual intervention is not possible when very fast decisions are required, for example when a sensor needs to be shared between many users in a short time span.

One way to construct an automatic resource conflict management system is to use a technique called Constraint Satisfaction Problems CSP, or Constraint Optimization Problems COP. Both may be realized in Constraint Programming Systems.

The basic idea behind these methods is to use solution techniques for equation problem solving. In such a solution, constraints and requirements are transformed into clauses in predicate logics. A set of such constraints is similar to an equation system. This is solved when each unknown variable has

1. IMM = Interacting Multiple Models

been assigned a value. An equation system may be under-decided, in which case it has many solutions, or over-decided, in which case it has no solutions. An optimization condition may be used to compute the best solution to an under-decided system.

In sensor management with multiple users and resource keepers, there are many agents. A resource keeper is responsible for maintenance and distribution of the resource; sometimes the term resource owner is more relevant. If the resource unit is open for usage by other users as well, the resource owner specifies the ways in which the resource unit might be used in a set of constraints, or rules, using a predicate logics notation e.g. Horn clauses. These constraints specify the allowed set of usages, and must always be true, according to the will and restrictions stated by the owner or keeper of the resource. This set of constraints is called the resource allowance set. Each user who wants to use the resource specifies in the same manner a request, which may be termed a usage constraint, in a Horn clause. The idea is now that the request is satisfied if the new constraint does not contradict the allowance constraint. Such a test is easily made by a logically robust software unit. Only if no contradiction occurs, the combined set of constraints yields a non-empty solution.

Conflicts at the sensor level

Conflicts at lower levels there the sensor mode of operation is selected could be handled by a set of rules. These rules defines that methods to try in a particular situation. For instance there might be less optimal sensor mode of operations which combines several others into one mode and therefore consume less resources. The drawback of using such a “rescue” mode might be less performance. Other actions might be to select less optimal parameters on scheduled sensor modes to consume less resources at the penalty of less performance. It is also possible to increase the delay between repetitive measurements or to completely cancel a low priority measurement.

Conflict summary

The suggested methods for resolving conflicting situations is a combination of established methods and “black-magic-art” selected by some set of rules. If conflicts can not be resolved by that, then the operators must handle the case. In section 3.6 and 3.5.3 we discuss conflicts in the context of planning and distributed agents.

3.4 Resource allocation

Resource allocation is an activity done on many hierarchical levels with different time scales. Resources are on a high level, groups of sensor platforms, on lower levels we have sensor platforms, sensors, some part of the sensor utilization and finally hardware resources needed for a sensor measurement or signal processing. Even communication bandwidth could be regarded as a resource. These resources should be used in the most optimal way in some desired sense. This resource allocation task is not simple and there is no guarantee to finding an ultimate optimum. The key is to subdivide the problem into more manageable smaller pieces which could be optimized independently.

We could identify a number of requirements on this function:

- The allocation process should be fast. Faster on levels close to the hardware.

- All users and processes needing resources must be handled by a common set of rules and a common method.
- These common rules and the common method should be supported by a service targeted towards resource allocation.
- There should be some space for initiatives from individuals. Individuals evaluate different resources differently and this should be reflected in the method.
- There should be some way of distribute the authorization among the users.

This resource allocation is always performed in advance to resource usage. Therefore, we need a planning system with a time schedule, see chapter 3.6. This is not a separate planning system, it is an integrated part of the total planning system.

3.4.1 A suggested approach

We suggest an approach with inspiration from the economic community. This method is currently rather loosely formulated and therefore needs a lot of refinements and modifications. It could be regarded as one of many possible ways of performing the allocation process.

In this approach resource allocation is considered as a game among users with different purified roles and tasks, see figure 3.2. All the users are primarily interested in their own roles and their tasks. They are also appointed some authority to execute their tasks but are otherwise playing by the same common rules.

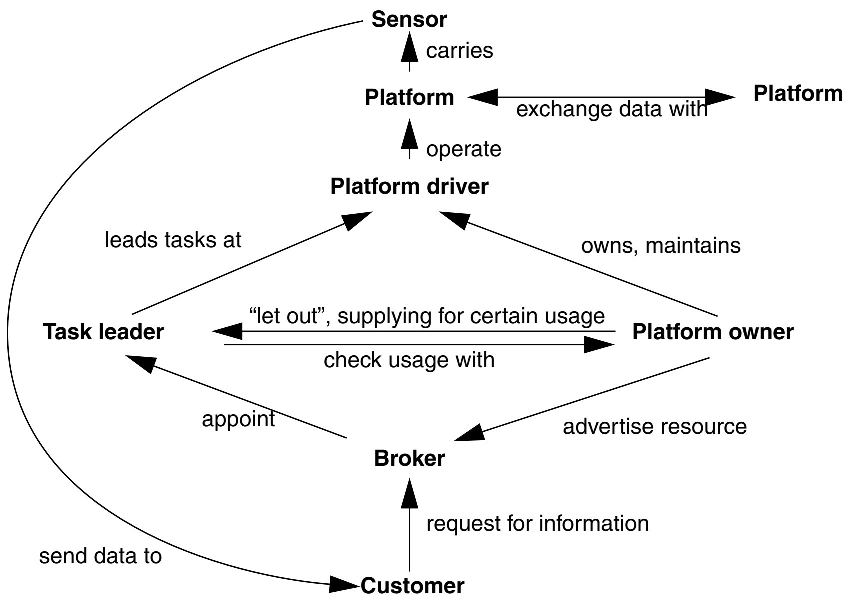


Figure 3.2: A roles game with several types of actors.

In this method the authority is achieved by the possibility to pay more for a resource. The user who is richest and/or perhaps most desperate win the bidding for a resource. This could at the first glance seem awkward in the military scenario but it is not as unnatural as it looks. We are dealing with some kind of *currency* that is used to pay for a resource. This currency can be based on priority, which implies that the most important mission is getting access to more currency and therefore more resources. The weakness is that when a new mission is defined, its relative importance have to be evaluated against *all* the other active missions. This requires a global update of all priority judgements in the system. This is not desirable due to its sensitivity to communication problems and also to the involved time delays. A consequence of this is that at a given time there will be many opinions in the network concerning the priorities of the current missions e.g. the system status may be unstable.

Another approach is to invent some form of fictitious currency for information gathering. In this case a mission is always given an amount of this currency for its execution. This amount will define the importance of the mission. The idea here is to let this "market" regulate itself according to a common set of rules. There are of course weaknesses with this approach also, for instance there have to be a circular flow of this currency within the system. This implies that a user can earn more currency by doing some good and rewarding actions. Failure to form this circular flow will cause the same kind of problems that we face in the economic world, inflation, deflation, good and bad times etc. A strength is that users with different roles are handled in the same way. Examples are the user out in the network who wants information from sensor resources to help him execute his military mission or the platform owner who is interested in maintaining his resource.

In the real case the model is multiplied for each resource class and distributed over the network. Also, there is a need for technical support of the model to speed up all actions that need to take place. It is also possible that some roles are more or less automatic, for example the broker or the platform driver. Their behaviour can be controlled by selecting policies.

Comments on the roles in the model

Every platform (with sensors) is "owned" by a user with the role of platform owner, which could be comparable with a lower level manager in a company organization. The role is to make the platform survive, plan its missions, protection and maintenance as well as inform the broker about availability, and capabilities.

Every information gathering task has a task leader which is comparable to a project leader in a company. He is an expert in information gathering and also negotiates with the platform owner about renting some amount of resource usage on behalf of end users, those who need the information.

The customer or the end user has a mission to execute when he needs information from sensors. The action when a need arises is to contact the broker which appoints a task leader and informs the customer and the task leader about available and capable resources. The customer orders the information gathering and negotiates with the task leader about the price for the requested information. The customer will receive the result as soon as possible when the requested information arrives at an successful task. Otherwise he will be continuously updated on the status of the task.

The spider in the network is the broker function, which can be distributed over the network and may contain automatic sub-functions as well as human operators. Its role is to keep track of which resources that are available, their status and capabilities as well as which task leaders that are available for new appoinments. He should also roughly estimate waiting times in case of overload.

The platform driver, which could be an automated process, drives the platform as decided by the plan and deliver the requested results to one or several task leaders. He is also responsible for certain automatic actions like self defence. The amount and type is controlled by the actual policy selected by the platform owner. The platform owner can be forced to select a certain policy type, e.g. high or low risk versus information quality, by the amount of currency or by direct order.

3.5 Distributed sensor control

3.5.1 Agent modeling

The theory of multi-agent systems (MAS) is a part of the fields of distributed artificial intelligence and robotics. One of the major ideas of the theory is to change the focus from centralized software to distributed software components that are autonomous in a certain sense. The autonomy is a result of the agents having their own goals and their ability to choose to perform actions when it suits them, not when determined by a centralized control mechanism. Autonomous agents do not imply that the system is impossible to control. Controlled performance of a joint system of agents is instead achieved by interaction among the agents. The design of a control mechanism for distributed control of autonomous agents is therefore also a question of designing the ways of interaction.

Agents

Based mainly on [24] an agent can be defined as a physical or virtual (software) entity

- which is capable of acting in an environment
- which can communicate directly with other agents
- which is driven by a set of goals
- which possesses resources of its own (e.g. money, some form of goods)
- which is capable of perceiving its environment
- which has a internal, uncertain representation of its environment
- whose behaviour tends towards satisfying its goals.

The capability to act in and perceive the environment, and not just to reason about it, is one of the discriminating capabilities of an agent vis-á-vis a classic AI-system[1]. Compared to any traditional software component, the autonomy is a distinguishing property, in the sense that they are not directed by commands from users or other agents but rather by their own goals. Also, the ability to communicate with each other is fundamental. A multi-agent system is an assembly of interacting agents in the same environment.

In some descriptions, the agents also have a set of *skills* and offer *services*. In that case, a skill is a description of a sub-task that the agent can perform.

1. AI-system = Artificial Intelligence System

Performing tasks may require both reasoning and execution of a sequence of actions. A service is a skill the agents can offer to other agents.

Distributed sensor control

Approaches that require a centralized functionality for sensor control have several shortcomings. Among these is the difficulty of allowing for local decision making and therefore to allow for initiative in the face of unanticipated and changing circumstances. Also, the continuous nature of decision making is ignored. In reality the actions chosen by operators on sensor platforms and of sensor control software are made continuously and in a detail that are hard to control from a centralized perspective. A system consisting of a set of sensors, mounted on platforms and operated by human users can thus not be seen as controllable from a centralized location without loosing flexibility, speed and accuracy in the decision making. Furthermore, limitations in bandwidth also limit the possibility of shared understanding in sufficient detail. That is, distribution of important beliefs may have to be filtered, resulting in discrepancies in situation pictures from central and local perspectives.

When automation of sensor control is required, some decisions have to be made by the sensor control component. Hence, the sensor and its control component can be seen as a form of agent. A joint system of operator and sensor control software can also be seen as an agent. The theory of MAS may consequently contribute to a theory of *distributed sensor control* that allows for initiative, quick response and localized awareness of the situation. In fact, distributed sensor control is necessary and must not be considered a problem from the perspective of sensor control. Risks associated with taking a decentralized perspective involve loosing the sight of the overall goal. As a general reference to a sensor and its control component the term *sensor agent* shall be used in the following.

3.5.2 Sensor coordination

Apart from allowing for distribution of control, MAS introduces theory where the focus shifts from the performance of the individual sensor agents to the performance of the joint system of sensor agents. One of the contributions of MAS is the development of theory for the interaction between sensor agents. By allowing the sensor control system to be viewed as a multi-agent system, issues of e.g. sensor cooperation and sensor competition can be readily introduced, see for instance [17]. Indeed, the theory of MAS introduces concepts of: *coordination*, *interaction*, *cooperation*, *competition* and *collaboration*.

Coordination, is the *process* in which actions of a community of agents are ordered to avoid resource contention and to allow the execution of tasks. Coordination can be to different degrees, which is the extent to which they avoid extraneous activity by reducing resource contention. Much of the field of MAS is concerned with coordination as determined by *interaction*.

Interaction, is any process that goes on between agents or between agents and their environment. Interaction can occur directly, via communication, or indirectly, via observation of the environment and action in the environment.

In much of the following, the discussion will be concerned with achieving coordination by means of deliberate communication. In MAS, communication between agents occurs when it is beneficial to the agents, not when prescribed by the system designer. This means that the formalized sharing of data and, notably, of control structures are the subject of study. Communication among sensor platforms are limited by the available bandwidth and localized control is a necessity to a certain degree.

Competition, is a form of coordination where the success of one agent means the failure of others. The most common form of competition is competition of resources, but also competition for services of other agents may appear.

Cooperation, is coordination among non-antagonistic agents where agents succeed or fail together, i.e. they have a common goal.

Furthermore, a group of agents form a *cooperative team* when

- all agents in the group share a common goal
- each agent is required to do its share to achieve the common goal
- each agent adopts a request to do its share.

Collaboration, is a form of cooperation which require mutual understanding and a shared view of the task being solved. That is, collaboration also requires a common view of the situation and of what actions that leads to the common goal.

Automation of coordination

Much theoretical development in MAS is focused on automation of the communication among agents. The decision on what should and should not be automated is an important issue when designing a sensor control system. Such decisions are very hard to make when considering future/experimental sensor systems, where neither the system nor even the final organization for their usage exists. It is also always the case that the introduction of new systems, e.g. a sensor or a system for sensor control, changes the ways the users perform a task or even the organization of work.

When not considering the complete automation of the communication, formalization of the language and the communication protocol can still be beneficial. One attractive feature with the use of a unified protocol of interaction is that it makes no assumptions of the decision mechanisms and internal reasoning of the agents. As long as the agents can respond in the appropriate language and follow the designated protocol, the interaction may result in coordinated behaviour. An agent where a human is directly involved in the decision making cannot communicate with a software agent without a strictly defined protocol.

A model for coordination

One mechanism for coordination is based on *computational economies* or *markets*. The research challenge is to build economies for solving problems of distributed resource allocation. In this approach, the major roles are played by Consumers and Producers. To specify a computational economy, one needs to specify:

- the goods being traded
- the consumer agents that are trading the goods
- the producer agents with their abilities for transforming some goods into others
- the bidding and trading behaviours of the agents.

Basing the method on computational economies means that the agents are assumed to be “economically rational”, which in turn often means that the agents are assumed to be self-interested. A self-interested agent wants to maximize its own utility. Being self-interested does not necessarily mean that the agents will not cooperate. However, they need a common goal to do so and the utility for cooperation must be higher than for taking individual actions.

If the agents are flexible and intelligent enough, the price of one of the goods will affect the supply and demand of others, since the market is interconnected. A market may reach *competitive equilibrium* such that 1) consumers bid to maximize their utility, subjective to their budget constraints, 2) producers bid to maximize their profits, subject to their capacity, and 3) net demand is zero for all goods. In general, the equilibrium need not exist or be unique.

In an open market, human agents do not have to behave economically rationally. Typically, economic rationality assumes that the agent’s goals are given along with the knowledge of the effects of an agent’s actions. The choice of action when the outcomes of actions are uncertain may be different, e.g. be risk averse. If there are no clear goals, the notion of rational behaviour is equally unclear.

The goal to maximize profit essentially requires that there is a scalar representation for all true goals of an agent. Whether a transformation of the true goals into a scalar representation is recommended or even possible is debatable. If the problem decomposition does not allow a credible, situation independent combination of goal evaluations into one scalar, the decision making must be more than straightforward optimization.

3.5.3 Sensor negotiation

In the theory of MAS, one of the most important processes in support of coordination is *negotiation*. Authors differ in their definitions of what constitute negotiation, but taken from [17]:

“Negotiation is a process in which a joint decision is reached by two or more agents, each trying to reach an individual goal … The major features of negotiation are 1) the *language* used by the participating agents, 2) the *protocol* followed by the agents as they negotiate, and 3) the *decision process* that each agent uses to determine its positions, concessions and criteria for agreement.”

Automated negotiation systems for self-interested sensor agents can be an essential component in a system for distributed sensor control. Negotiation is a method that can be used for resolving conflicts, but also for achieving cooperation. If the goal is common, negotiation may still have to be performed in order to reach an agreement about which agent that will perform what tasks.

The importance of negotiation is proportional to the dissimilarity of the agents. The less the agents can take for granted about each other, the more important the negotiation becomes. Protocols for voting, auctions, bargaining, markets, contracting and coalition formation exist. Looking at the architecture of figure 3.2 a function for negotiation may be important for a broker in the system. A broker is typically called a mediator in the terms of MAS.

In general, agents that follow a protocol for negotiation create a *deal*, which would satisfy all, or as many as possible, of their goals. A deal can be seen as a joint plan for (re-) assignment of tasks among the agents. The *utility of a deal* for a consumer agent is the amount the agent is willing to pay with exclusion of the cost of the deal. Both the agents own valuation of the deal, as well as the agents available amount of money must be taken into account when determining how much the agents are willing to pay. For the producer agent, the utility of the deal is the amount of money that can be earned from the deal excluding the cost of performing the task. The negotiation process results in a negotiation set, which is the set of all deals that have a positive utility for every agent, i.e. the deals that are individually rational and Pareto[1] optimal.

Team creation

Naturally, some mechanism must exist which can determine which agents that exist at all or that are relevant to the solution of a certain task. This could be handled by a mediator with the responsibility to create a team of agents that is available and with the appropriate skills to perform a task. The actual coordination could then be performed by negotiation among the designated agents. Such a mediator would also need to handle failure to respond (does the agent still exist?) and the uniqueness of identity of agents (is this the same agent?).

Negotiation in sensor cooperation

In the article [29], the authors describe a multi-agent system for allocating resources while satisfying constraints in a real-time environment. The application is multi-sensor target tracking, i.e., the agents resources are sensors which are allocated to tracking tasks at certain time-intervals. Agents negotiate to find a solution to the joint “goal” of optimal accurate and effective tracking.

The solution requires the agents to be reflective, i.e. they must be aware (to a certain degree of accuracy of course) of the amount of available resources and how their actions affect their resources. In this case the resources are primarily in the shape of *time at the sensor*. That is, the time that is required and available at the sensors in question. An accurate judgement of this quantity is not uncomplicated and 100% accuracy is impossible. Thus, the actually consumed resources may differ from the predicted and those taken payment for. Naturally, a task may take different amounts of time depending on when it is performed, e.g. due to the geometric and physical characteristics of the situation when the task is performed. Furthermore, the outcome of sensor actions may be different than hoped for. There must consequently be some spare time to repeat the performance of actions if not an excessive re-planning shall be necessary.

As mentioned above, the agents in [29] are assumed to have the same goal. They are also assumed to have the same reasoning mechanism. This means that an agent can predict the decisions and actions of another agent, given the same information as the other agent. Only dissemination of the right information is needed to predict the actions of others and therefore also to ensure the desired actions of other agents. On the other hand, it may require explicit sharing of the performed reasoning if the agents reasoning are too heterogeneous. Such sharing of reasoning mechanism can never be

1. Pareto optimal, In an endowment economy, an allocation of goods to agents is Pareto Optimal if no other allocation of the same goods would be preferred by every agent.

complete if the agent is comprised of a human user as well as the sensor component. This is exactly the reason for joint training of personnel while at the same time being a major source of difficulty when cooperating e.g. across cultural borders. Note that *sensor cueing* can be considered a special case of the sharing of information. If one agent knows that another agent needs some information, it may initiate a negotiation on the other agents' behalf.

The negotiation mechanism of [29] can be described as follows. Agents can assume two different roles in the negotiation, *initiator* and *responder*. After an initiator decides that assistance is needed in tracking a target, it establishes a set of negotiation partners, a *coalition*, and contacts them to start negotiating. The initiator sends a message requesting a resource and a time-interval it needs the resource. A responder determines if it can comply immediately, if it can negotiate or if it can not negotiate and thereafter answers accordingly. In the paper [29] the agents must then automatically select a negotiation strategy, which it does using case-based reasoning. However, most automated negotiation systems employ a fixed strategy for its negotiation. If a negotiation is possible, the initiator attempts to persuade the responder by sharing parts of its information or its current workload. The reason for sharing of workload may result in the responder performing a task that all agents in the system have a joint goal of efficient tracking and therefore strives to accomplish an even distribution of workload.

A similar approach to sensor coordination is advocated by Durrant-Whyte [28] and co-workers, who describe cooperation between sensor carrying UAV:s. This approach also builds heavily on the commonality of the information processing of the sensor platforms. The communication between the platforms only involves the distribution of information and not of any control structures. A common goal is assumed and a shared view of the optimal actions is ensured by the similarity of the processing at sensor platforms. Other excellent papers on sensor cooperation by market mechanisms are [26], [7], [27]

Conflicts

Sensor units may be shared among several users. Sharing a sensor usually requires manual negotiations every time different users want to use the same resource, at least for hardware resources. If a hardware resource is wanted by more than one user at the same time, there is a conflict and a conflict resolution mechanism is necessary. An alternative to manual intervention is an automatic conflict resolution system. Manual intervention is not possible when very fast decisions are required, for example when a sensor is shared between many users in a short time span.

Conflicts occur at many levels of sensor control. Increase in capability of the sensors allows more functions to be performed in one sensor. It is inevitable that conflicts will occur between the different functions that a sensor can perform. The connection of sensors to a network where the sensors can be used by many different users increases the risk for resource contention. Negotiation is applicable to resolve conflicts in situations where sensor agents may have different goals, and each agent thus is trying to maximize its own good without concern for the global good. In this case, the protocols for interaction play an important part in the functioning of systems of such agents.

When considering negotiation on which task to perform among several alternatives, many types of tasks raise issues of goal formulation and measuring goal achievement, i.e. what is good enough and when have we reached our goal? A loosely formulated goal of "performing the task as good as possible" is clearly not enough. In order to reach suitable compromises between different needs, a performance level other than "as good as possible" must be defined. Otherwise the usage of sensor resources is still going to be inflexible and with very limited room for exploitation of opportunities as they arise. Multi-tasking of a sensor will also be difficult to achieve.

The considerations of tasks that need to be performed simultaneously indicate the need to compare the importance of completing tasks of very different character. Successful sensor control implies not only the need to measure the degree of success to which a task is performed. It must also be able to predict that degree if feed-forward control is to be possible, i.e. if the control shall be planned and not just reactive.

A further complicating circumstance is the ability of a combination of sensor platforms to perform a task in many different ways and to different degrees of success. In [18] the authors suggest a definition of a finite and pre-established set of performance modes to delimit the number of ways a task are allowed to be performed. In this case a centralized mechanism must be responsible for the selection of performance mode. A performance mode can be both individual to a sensor, e.g. a target illumination by an active sensor, and joint, e.g. joint triangulation by a set of passive sensors.

Conflict management by constraint techniques

One way to construct an automatic resource conflict management system is to formulate the problem as a Constraint Satisfaction Problem CSP, or Constraint Optimization Problem COP. The basic idea is that all sensors and users constrain the usage of the sensors in some way. A user constrains the desired performance of the system by their requests to the system and the sensors by their possibility to perform an action. All actions that satisfy the constraints are allowed.

In some approaches, constraints and requirements of different agents are transformed into clauses in predicate logics, see section 3.3. This set of constraints is called the resource allowance set. Each user who wants to use the resource in the same manner specifies a request, which may be termed a usage constraint. The idea is now that the request is satisfied if the new constraint does not contradict the allowance constraint. Such a test is easily made by a logically robust software unit. Only if no contradiction occurs, the combined set of constraints yields a non-empty solution.

When modelling the problem as a constraint satisfaction problem, only hard constraints - with values FALSE or TRUE - are used. The penalty of breaking a hard constraint is infinitely large, while the penalty for not breaking it is zero (0). This is not sufficient when reasoning on the constraints is needed, as it is for example when different constraints have different intentions, reasons and characters. Soft constraints will then allow other values than 0 or infinity. Breaking a soft constraint will yield a value between these values. The optimal solution of a set of soft constraints brings with it the least possible cost, and indications of which constraints that are broken. In the general case there may be many constraints to satisfy. Only some of them are soft.

Strategies for finding solutions to systems of soft constraints have been investigated elsewhere. Verfaille et al. [20] describes the problem as a search problem, where the search refers to a search of ordered variables to solve. In the general case one variable is selected each step, but [20] proposes a set of variables to solve at each step. In [21] an alternative search method called Weighted Constraint Satisfaction is proposed, since it allows the user to assign a cost to each constraint. Reference [23] makes a similar study of CSP. In [22] an AI-based method is proposed.

Contracting

The contract net protocol represents an attempt to solve the problem of *distributed negotiation in task allocation*. While the original contract net protocol was designed for cooperative agents, extensions has focused on competitive agents. One case of competition being between many producers that compete for the right to perform a task, and thereby to earn more money. According to Ferber [24], the contract net protocol is a control structure which is very easy to understand and to use. The major roles are played by the *manager* (also consumer) and the *bidders* (also producers).

The relation between the manager and the bidders is channelled through a request for bids and an evaluation of the proposals submitted by the bidders. An agent can be either a manager or a bidder in the performance of different tasks. The process has four stages:

(i) The manager sends a description of the task to perform to all it considers able to respond.

(ii) On the basis of this description, the bidders generate proposals which they submit to the manager.

(iii) The manager receives and evaluates the proposals and awards the contract to the best bidder.

(iv) The bidder which has been awarded the contract and therefore becomes the contractor, sends a message to the manager signalling whether it is still willing to carry out the task. If not, the bidding must resume.

Ferber defines the different types of messages, e.g. propose-message, accept-message, that are needed to implement a contract net protocol. The communication that has been described so far is rather elementary, but extensions of the protocol have been suggested by Smith [30] that also includes e.g. the required quality of the task and an expiry time of the proposal.

The relative simplicity of the protocol obscures some of the difficulties of the process. In particular, the formulation and evaluation of proposals are not addressed. Extended mechanisms, using new cycles of refined proposals and counter-proposals instead of directly awarding the best bidder the contract in step 3 above, are easy to imagine.

Auctions

The dissertation [25] is concerned about the intelligent coordination of large-scale synthetic systems, focusing on networks of sensor-actuator nodes. The goal is to provide methods that achieve efficient, scalable and fault-tolerant cooperative behaviour in networks of such nodes. Specifically, he argues for the use of algorithms for distributed auctions for the allocation of resources. He show that such algorithms can be effective in coordinating small teams of mobile robots. As earlier mentioned, one attractive feature with the use of a unified protocol of interaction is that it makes no assumptions of the decision mechanisms and internal reasoning of the agents. As long as the agents can respond to requests and formulate bids in the appropriate language, the negotiation may result in a favourable allocation of tasks.

Critical user aspects

In the NCW concept, ordinary users employ abstract services to get a surveillance system to perform the tasks they need and thereby to get the information they need. In such a case, the user is generally seen as being outside the control loop of the system. It is assumed that most users do not have the time or expertise to either interpret or control the system to a satisfactory degree while at the same time being occupied with more immediate and pressing concerns. Hence, a user does only affect the system by initiating requests to the system, which (hopefully) are responded to and executed by the system. In order for the user to be aware of the progress of the task, a task completion level must be measured and communicated. Otherwise, new requests may be unnecessarily issued to the system and risks to saturate the system. A solution that hinders a user from issuing requests or changing the requests earlier issued is probably unacceptable.

Using computational economies as a model for resource allocation is a promising approach whose general applicability is hard to match. Still, an important issue that needs resolving is how human users involved in the economic system can know the value of their “money”. If the money is not grounded to anything the users can relate to, the value of the money may be difficult to understand. What is expensive? What is cheap? Even what the real incentives are for a human to participate in the solution of a task if the only reward is some abstract money can be an issue. The potential to earn a lot of “money” cannot be enough if it does not translate into a transparent advancement in the pursuit of a common goal. If the consumer does not even have the same specific goal as the producer i.e. the consumer and the producer do not belong to the same team during a specific mission, the negotiation must be handed over to a higher level of authority.

Too little or too much money for some users would lead to a system where some tasks is performed unnecessarily well at the expense of other tasks. If the computational market is advanced enough, the total amount of money will however not affect the resource allocation as the producers will adapt the prices to meet the demands. The unfair distribution of money among the consumers will still result in a poor allocation of resources.

Available money

To agents with a common goal, the amount of available money to solve a task should be proportional to the extent to which the completion of the task supports the pursuit of a goal. Formulated in other terms, the predicted improvement in the quality of the decision should be the basis for money, see Appendix C. This is of course a quite difficult quantity to calculate. If partial solutions are acceptable, the goal can instead be formulated in simpler terms e.g. in the terms of uncertainty. That is, the amount of money available to a consumer is proportional to the uncertainty of the state estimate. Given that the agents all estimate their uncertainty in same manner, a system where the producers maximize the money they can earn would also be an uncertainty minimizing system.

Cost estimation

Cost should be physically grounded if possible. In many cases, it is *time* that is the basis for a cost. The cost of getting a producer to perform a task should at least depend on the estimated time to perform the task at the sensor in question. The time left in the schedule during the requested time interval is also relevant to the cost. Additionally, if the performance of the task requires actions that place the sensor and its operators at more risk than otherwise, the cost should increase. For instance, moving to a location closer to a known threat or using active sensors that adds to the risk of exposure.

Given that the cost is dependent on time, the more money that is earned, the more the sensor has been used. If the amount of money the consumers are willing to pay are correlated to the likelihood of success to a common goal, the amount of money earned is correlated to the contribution of the sensor agent to the agents own goal. The amount of earned money may thus actually serve as a performance criterion to the operators, perhaps even as an evaluation criterion.

Note that a system that is risk neutral - while its users are not - may be difficult to trust. As the risk in the types of missions that are performed by military platform operators may be a big risk to the lives of the operator, the assumption of risk neutrality should not be up to the designer of a sensor control system. The operators on sensor platforms must be able to determine the risk they are prepared to take. Also, the situation may be different than expected. If e.g. the situation is more threatening than expected, the operators should have the authority to abort a mission. Of course, if we are talking about the risk of loosing some abstract money whose value are difficult to judge the situation may be the opposite. Unmanned vehicles may be more naturally risk neutral.

3.6 Multi time-scale planning

It is possible to regard the sensor control problem as a planning problem. It is a hierarchical planning problem where the planning with long time-scale is very coarse, but are further refined on each lower planning levels as the time-scale decreases. Higher planning levels may also contain parallel activities. One example is on a multi sensor platform where each sensor operates in parallel and the planning on platform level have scheduled all sensors to different higher levels tasks. On each planning level there is a possibility of rescheduling when new activity requests occur. This process has consequences on planning levels lower than the current as they have to answer questions about expected load, closest possible time etc., apart from doing rescheduling then necessary.

The planning on a given level is performed using a set of rules and requests or events. Another aspect is the status of planned activity in the future, status like *preliminary*, *stand-by*, *confirmed* etc. This status controls the effort that is used when estimating costs and usefulness for a given activity and therefore the effort in trying to schedule the activity in question. Figure 3.3 shows a picture with planning on three different levels and time-scales but without overlaps in time.

In this multi level planning process it will be very important with feedback between levels, especially the scheduled time and the reasons for delays. Later rescheduling will also cause feedback in case of major changes in time or estimated cost. Conflicts is handled by a set of rules which describes the

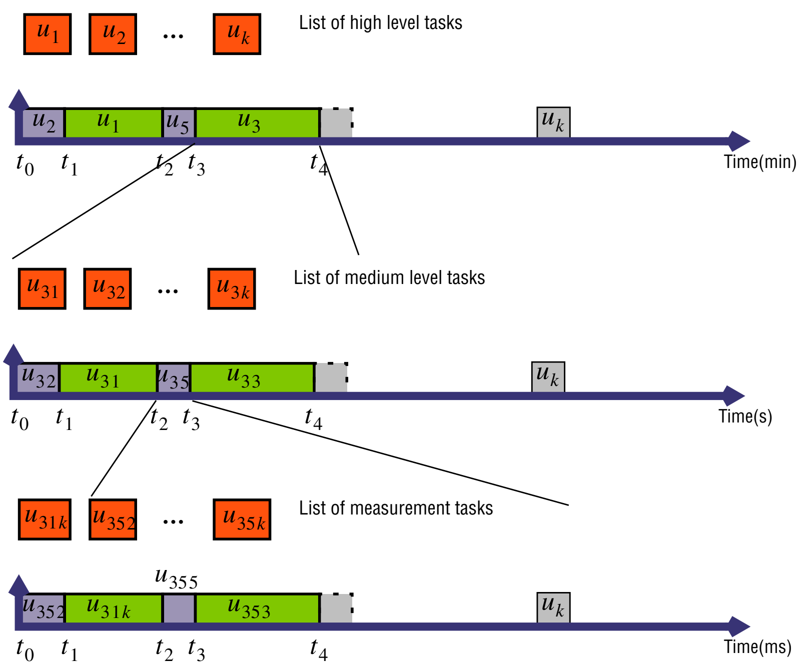


Figure 3.3: Different levels of planned schedules. Feed-back between the planning levels is important to handle the different time-scales in a reasonable way.

actions to be tried. However, some conflicts will be impossible to handle on the current planning level and will therefore be sent to the next higher level as an conflict event to be handled. It is therefore possible that a conflict event can propagate up through the planning levels to be handled by the operator at the top level in an extreme situation.

As the goal function for the whole planning process is very complex with many dimensions it is also difficult to understand the large picture. A rescheduling of a task from one time to another may cause the estimated cost for that task to change dramatically.

The planning problem is also a scheduling problem. This scheduling problem for the shortest time-scale at the sensor have been described in several paper, see [3], [4], [5] and [6]. The suggested methods are based on dynamic programming and rule-based heuristics.

3.7 Distributed functions and communication problems

In order to communicate between nodes in the network there is a need for reliable communication links. The status of those links in terms of on/off, estimated bandwidth etc. is an important factor in the process of planning and also in fault analysis problems. However, this is not the focus of this report, we just note the importance of this area.

A consequence of communication links with a variable and sometimes low bandwidth is that the sensors must have the ability to adapt to the situation. This means that a sensor should be able to deliver data at many abstraction levels, in principle at the same time, see figure 3.4. In difficult communication situations it is preferred to send data on as high abstraction level as possible.

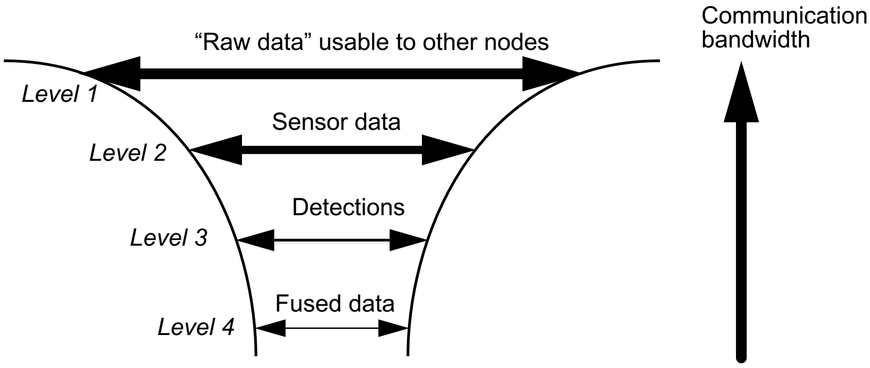


Figure 3.4: Sensor reports on several abstraction layers. Data can be delivered to the network at different processing levels depending on situation and available communication bandwidth.

3.8 Information quality

The question of information quality can be viewed in different ways. For the end user it may seems simple, namely that presented data should be reliable. However, by putting too high demands on the information, valuable but uncertain information may be ignored or neglected. Also, the information may be accurate and precise, but not so easy to present. If the user misunderstands the information presented, the information quality is, from a practical point of view, low. On the sensor side, the information quality is, more related to the hardware and the signal processing, so that a certain signal being over a given threshold is interpreted as a true indication with some given, i.e., model based, probability and as a false target with some probability.

Between these two endpoints, information has to be condensed by some automatized reasoning. The output of a sensor network aided by computer based rules for information fusion, will be very sensitive to the nature of these rules. The issue of how to formulate these rules is central, and there is a multitude of suggestions of how to formulate appropriate rules as we saw in section 2.5.1.

For instance, there are known examples, e.g., Dempster-Shafer theory, where simple situations give rise to counter intuitive conclusions. Also, attempts to model uncertainties in detail give models which are too complex. In addition, the difficulty of presenting the information grows.

3.9 Sensor control in autonomous UAV surveillance with EO/IR-sensors

When an autonomous UAV is used for surveillance and reconnaissance the problem of controlling the path and sensor must be solved in an intelligent manner. Concurrent sensor and path planning, taking into account both platform and sensor constraints as well as threats and environmental conditions, is a very demanding task. Even more demanding is the capability to dynamically adapt and re-plan the sensor utilization and the platform trajectory in response to changes in the environment.

The research field of UAV path planning and cooperation attracts a lot of attention and the number of publications is rapidly increasing. However, the problem of concurrent path and sensor planning is still a rather unexploited area. An introduction to the UAV surveillance and reconnaissance problem is given by Ulvklo et al. in [23] where the path and sensor planning challenges in UAV surveillance are discussed. Nygårds et al. [32] give an overview of research fields and communities related to path planning and/or sensor planning. The report also includes a survey of methods, techniques and approaches to path and sensor planning.

One of the methods, an information-theoretic approach, proposed by Grocholsky in [20], is analysed in depth by Skoglar et al. in [22]. Although information-theoretic approaches have been applied to path planning problems before, the focus on concurrent sensor and path planning is new in [22].

3.9.1 Surveillance Tasks and Operating Modes

Surveillance information service would require allocation of accessible surveillance resources to meet the request for new sensor data. The provider of the surveillance services is the signal processing and control system onboard the UAV itself, or related ground stations, depending on the level of autonomy of the system. However, planning, synchronization and management of surveillance resources over a larger area-of-responsibility is a very demanding procedure. A client/server approach, designed for managing adaptable surveillance missions, is introduced in [23]. The framework is based on a relationship between information consumers, who dispatch surveillance client requests, and a service provider, responsible for surveillance server responses.

Surveillance services can then be divided into different objectives, tasks, requests and search patterns. They can be divided into two classes of request modes, *surveillance & search* and *tracking & data acquisition*. *Surveillance & search* in turn can be divided into area search, strip search, line search, and pinpoint. *Tracking & data acquisition* involves multi-target tracking, precise target coordinate generation, and detailed ROI[1] data acquisition. To successfully plan and perform these tasks autonomously, some operating modes that facilitate the planning and navigation are also required. Thus, we introduce a *Planning & navigation* support mode that builds and maintains a world model that the planning optimization and navigation estimation are based on. This mode is, for instance, performing probing actions, occlusion estimation, obstacle detection and map building.

Hence, we have three classes of operating modes:

- Surveillance & search
- Tracking & data acquisition
- Planning & navigation support

At the sensor level only one mode is executed at a time. However, several tasks requiring different modes may simultaneously be requesting the sen-

1. ROI = Region Of Interest

sor resource, and the planning must therefore incorporate some kind of sensor scheduling to allow the system to quickly switch between different modes. The planner does not necessarily require an explicit scheduler; approaches may exist where the scheduling behaviour is a natural part of the planner framework.

3.9.2 Planning Constraints

The planning optimization process is affected by planning constraints. Six classes of constraints are identified in [22]:

- Platform constraints are associated with the UAV platform, such as dynamic, kinematic, nonholonomic, and fuel constraints.
- Environmental constraints define areas where the platform cannot or should not be placed or pass through, and thus include geometric constraints, accessibility constraints, obstacle avoidance, and threat avoidance. Also the level of acceptable autonomy belongs to environmental constraints.
- Viewpoint constraints define areas where visibility is reduced relative some task, for instance due to occlusion, distance, and viewing angle.
- Sensor constraints are associated with the gimbal, e.g. dynamic and kinematic constraints, and to the sensor itself, such as field-of-view, resolution, and contrast.
- Target constraints are associated with properties that affect the detectability of the target, e.g. target motion and pixels over target.
- Timing constraints affect all aspects of planning from platform to sensor.

3.9.3 Path and Sensor Planning Levels

In [22], different airborne surveillance tasks can be divided into four different search patterns. Consider a line search example, road surveillance. This involves searching for targets along a road and gathering detailed information, such as high-resolution images, georeferenced position, of detected targets. Problems in this surveillance task can be threats and occlusion due to trees, buildings, or terrain masking. The controller must be able to handle uncertainties, such as partially unknown occlusion and road position.

Prior information, e.g. GIS data and prior imagery, Figure 3.5 (a), is useful in the initial planning 3.5 (b), but as the surveillance process progresses it is necessary to look ahead 3.5 (c) and adjust the plan 3.5 (d) due to uncertainties and errors in the prior information. Performance measurements are needed to verify mission success. For instance, a high detection probability can be achieved without necessarily covering every square meter of the road or the ground.

A successful solution to the road surveillance scenarios above should display properties such as probing, caution and reactive behaviour. Probing represents actions to enhance estimation precision in order to improve overall performance in the future. Caution is acting so as to minimize the consequences of erroneous assumptions about the state of the environment. Reactive behaviour means adapting to changes in a dynamic and uncertain environment, e.g. focusing attention on detected targets. Probing

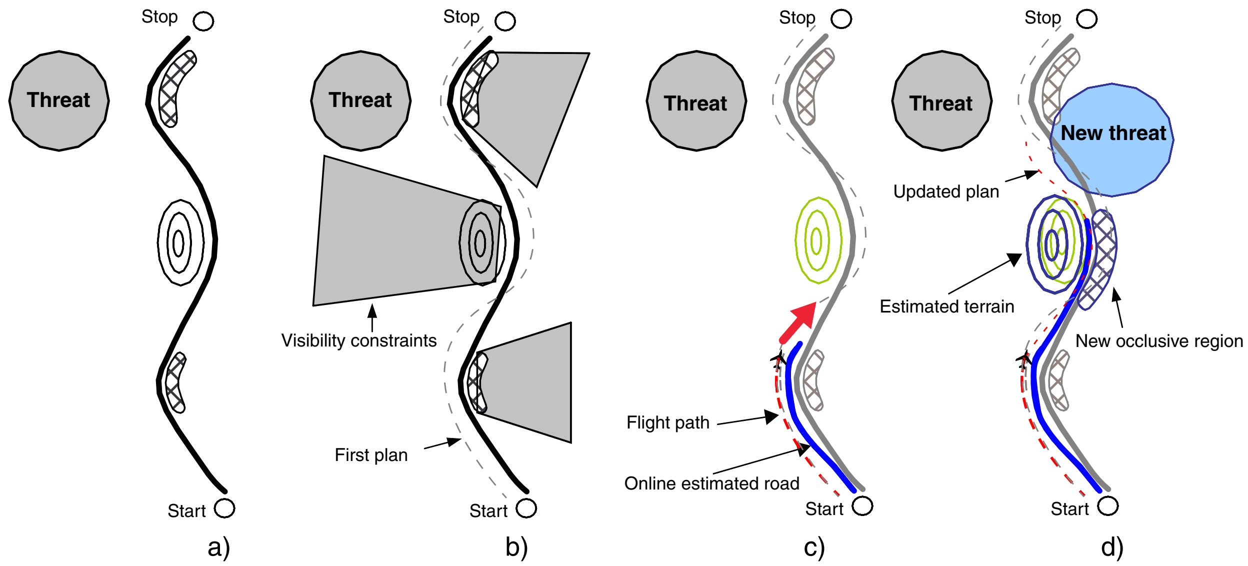


Figure 3.5: Road surveillance scenario. (a) Prior information. (b) Initial plan based on prior information. (c) "Probing", i.e. look ahead and update the world model, is necessary. (d) Re-planning is required by newly detected visibility and environmental constraints.

and caution are properties of dual controllers as described by, for instance, Maybeck [21].

This discussion motivates a decomposition of planning into the following functional and temporal hierarchy:

(i) Long-term platform path planning considering prior knowledge, threats, pre-planned surveillance requests and time constraints.

(ii) Short-term platform path planning and long-term sensor planning, considering the long-term path plan, trajectory smoothing, detected threats, visibility, occlusion, probing, collision avoidance, and dynamic surveillance requests.

(iii) Reactive platform path planning and short-term sensor planning, considering the short-term path plan, trajectory smoothing, occlusion, collision avoidance, and gaze planning.

(iv) Reactive sensor planning, considering focus, zoom, contrast, and gaze in addition to the superior path and gaze plan.

The long-term path planning (level 1) is primarily deterministic and can be computed off-line. This plan might be manually prepared. Also the reactive sensor planning (level 4) may be considered separate from the other levels. However, the levels 2-3 represent a very challenging problem due to their stochastic nature, on-line computational demands, and reliance on sensor data analysis. Also, there is a strong coupling between the sensor and path planning, as well as between the planning levels. Consequently, the planning for levels 2-3 must be considered as one single problem. In this section we have only considered a line search example. The discussion here can also be applied to the other search patterns; area, strip, and point. Results on implementations of this planning decomposition, taking into account constraints such as occlusion and limited field-of-view sensor models, are found in [22].

3.10 Similarities with other problem areas

We have found some similarities with other areas, at least to some extent.

- Production planning. Here we find similarities in the planning problem of complex logistics. There are many productions plants, many machines, production lines and a complex flow of material where everything should arrive just in time. The production planning is somewhat less dynamical compared to sensor control but there are more nodes in the system.
- Telecommunication routing. The similarity is the distributed complex goal function. This problem is more dynamical than the previous one in the case of mobile nodes.

In the work done in [1] *towards autonomous UAV surveillance with EO/IR-sensors* the authors identified a web of research areas that have impact on their problem, see figure 3.6. This web is also valid for the more general sensor control problem but it needs to be extended with some new areas like distributed multi agent systems.

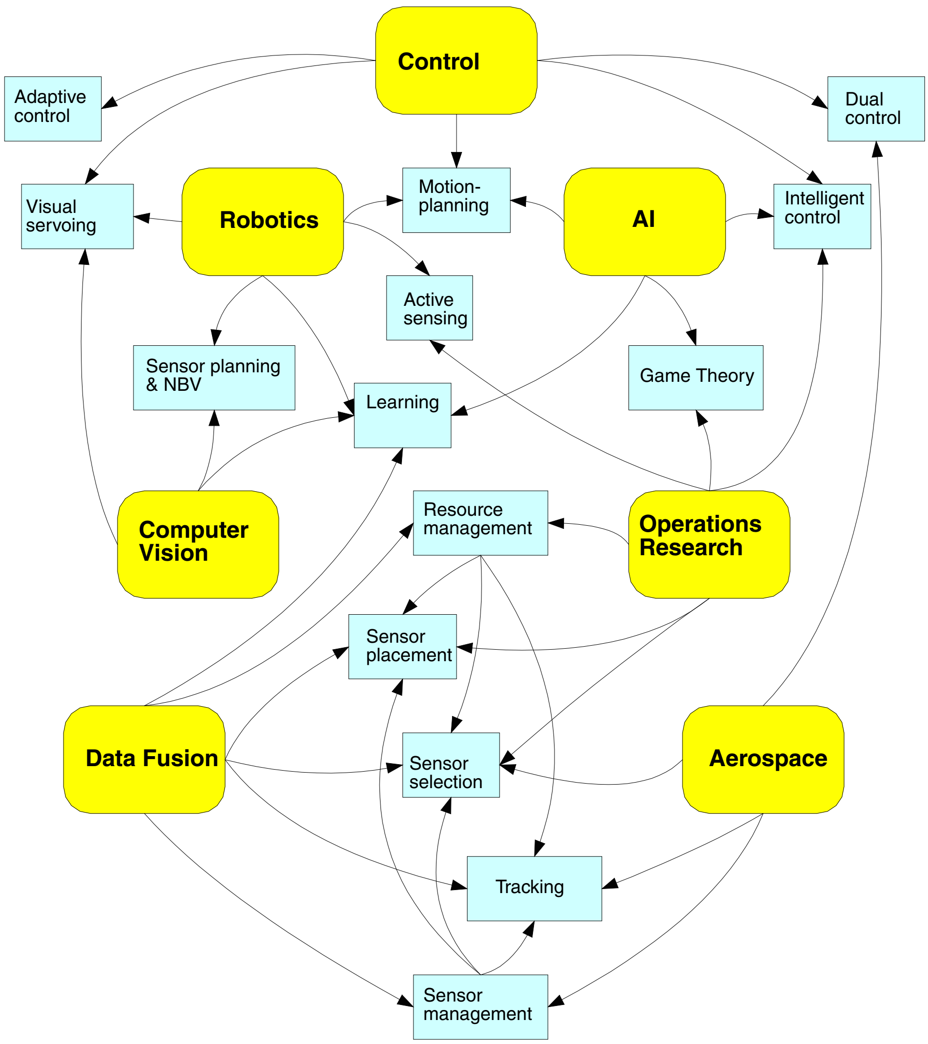


Figure 3.6: The wide web of planning fields and communities.

4. Assessment of systems including sensor control

System assessment is often a difficult issue, especially when the system consists of many components and the goal of the system is not very well defined. In this section we will primarily discuss sensor control systems and sensor management systems that are automated. The reason is that systems in which man is not an essential part of the system are usually somewhat easier to assess and to compare.

As discussed above sensor control and sensor management can be performed on different levels. An example of a sensor control problem on a low level is how to place one single platform such that its sensor is optimally located for detection of targets within a certain area.

A sensor control, or rather a sensor management problem, on a somewhat higher level is how to support several military units with information in best possible way, when using a limited number of sensors placed on different platforms. Assessment problems can be put into two categories. The first category consists of problems for which the issue is whether one should enlarge an existing system with a new component - a new technique - or not. Assessment problems in this category lead to one of two possible decisions. Either the new technique is added to the system or it is not added.

The other category of assessment problems consists of those problems for which there are a set of new techniques each of which is a candidate to be added to the system, and each of which having its advantages and disadvantages to be assessed. A difficulty with all assessment problems is that often the persons that develop a new technique are not the same as those using the new technique. Thus, there are often two groups of experts involved, the user experts and the producer experts, and usually these two groups of people are disjoint.

The common way to assess systems is by looking at one or two or more *assessment variables*. An important assessment variable in most situations is the price. The cost for adding a new technique to a system can never be completely overlooked.

A large group of assessment variables can be called performance variables, which are variables which describe how the system or part of the system perform. A difficulty however when deciding upon performance variables, and assessment variables in general, is that the choice of performance variables can vary a lot between user experts and producer experts. It is therefore important, when developing new techniques that will be added to an existing system, that the performance variables that the users are interested in, are taken into account by the producers.

Performance variables that are natural to choose when assessing sensor control systems are for example, the number of detections, the number of correct identifications of hostile vehicles and/or aircrafts, the number of false detections, the estimated number of lost platforms due to different levels of enemy activity (the risk of being shot down), the amount of fuel used. The performance variables just mentioned are essentially user oriented. Producer oriented performance variables can for example be computation times, computer sizes, bandwidth.

Sensor adjustment to current conditions of measurements are necessary for any kind of sensor processing made by an intelligent sensor. Otherwise no interpretation of collected data is possible. For inflexible sensors there are few adjustments, and few interpretation alternatives are at hand. For flexible sensor systems, more adjustments are necessary in order to constrain the number and kinds of alternatives for interpretation. This requires more a prior or in-house information.

4.1 Comparing different sensor control systems against each other

Different sensor control systems can be assessed by comparing quantifiable measures.

Examples of such measures are quality improvements, functional extensions of the sensor system, safer or stronger tactical behaviour, see e.g. applications of sensor chains and costs, including time resources, to do adjustments of the sensor system.

Examples of measures used in sensor systems are:

(i) Improvement of tracking quality after using target type information. In an ESM[1] system, signal parameters from targets using passive ESM sensors are used both to infer type information and target state information, including track parameters as position, velocity and state. First, targets are classified and assigned vehicle or target type data. Then this information is used to improve the track quality. For example, targets which are classified as ground vehicles are tracked using target models applicable preferably to ground vehicles. The improvement of tracking quality is clearly a measure that can be used to assess a sensor management system.

(ii) Target classification can be improved by using sensor management of mm-wave radar and IR. Image features achieved from the mm-wave radar may be used to direct the search for image features using the IR sensor. The improvement in target classification is an objective measure which can be used to assess a sensor control system.

(iii) Capacity improvement in detection and tracking using radars and IRST[2] sensors in a network: The radar is focused on task types where the radar has unique capabilities, when other sensors can take over some of the other radar tasks. This may be used to increase the radar's detection range or detection probability against small targets, see [8]. These measures can be compared.

(iv) Sensor management of sensors in a sensor network may be used to make the sensors more agile. Agility varies with the sensor type. For an AESA[3] radar it means resolution in bearing, range or range rate. For an ESM sensor it may mean higher resolution in frequency which brings higher quality concerning bearing, type and waveform measurements.

(v) Tactics might be changed as a result of introducing sensor management. See for example point (i) above. For example the use of the concept of multiple platform ESM sensors requires that the "other

1. ESM = Electronic Support Measures
2. IRST = InfraRed Search and Track
3. AESA = Active Electronically Steerable Antenna

side" starts using radars on each platform. In order to force them to do so, a jamming activity is needed from our side to disturb the radar of their surveillance platform. This will force each individual to start its radar in order to get a situational awareness (SA). So the tactical assumed process is: (a) Side A jams the surveillance platforms of side B, (b) Side B loses its SA, (c) Individual platforms of side B lighten up their radars in order to reassure individual SA, (d) Side A listens to the radars and start to analyse the radar data using their passive-only ESM sensors, (e) Side A platforms track targets in side B using ESM data.

4.2 Comparing a system with sensor control with a conventional sensor system

The first problem is to do fair comparisons between sensor systems, that use different amount of resources. Is the limiting factor the total price on the system, or it is the number or maybe the quality of sensors and other nodes in the system? Some issues are very hard to put a number on and use as an assessment variable, for example, how does one value flexibility? Implicitly, this is the evaluators belief of how the future will be, which have to be taken into account by a method.

4.3 Specification and verification

Another similar problem arises when a procurement agency is about to purchase equipment with sensor control or software that implement some aspect of sensor control. The problem is then how to specify functions and functional behaviour so that it could be understood by the suppliers and also be tested when the functionality is delivered. This is problematic because it is impossible to test all possible cases since the complexity, uncertainty and timing cause a combinatorial explosion of test cases. Also, the behaviour in this kind of system, depend on the dynamical situation and could be highly load dependent.

A new methodology is necessary to address this issue. We believe that such methods should be based on probabilistic specifications with some kind of way to identify the worst and best cases and how probable they are.

One way forward can be to specify a rather small amount of typical situations which are widely spread in terms of the volume of usage situations, and then specify assessment variables and their variation in relation to disturbance (or perturbation) of the situation in question in statistical terms. These figures can then be verified by simulations of the complete system. The last step will be to test one or two small situations in reality.

The described approach is very different from approaches used today because it is based on probabilistic figures and not absolute worst cases limits which should not be violated.

5. Application areas

5.1 A military scenario

This scenario is a typical ground surveillance scenario where we are using several sensor types mounted on different platforms. Many of the platforms are airborne while others are placed on the ground. There could of course be many smaller variations on the concept so it need not be exactly as described here.

Ground surveillance with sensor systems is a very demanding task due to the varity of target types, complex sensor backgrounds, a multitude of non-military targets and varying weather conditions. No single sensor system can fulfil all kinds of information requests during a ground surveillance operation but there are several sensor technologies available with complementary features. Our approach is to use the different sensor systems in an intelligent way, adapted to the situation, and combine them to fulfil the information demands from the operators. This scenario is also used in the FOI project SEMARK, see [19], and is illustrated in figure 5.1.

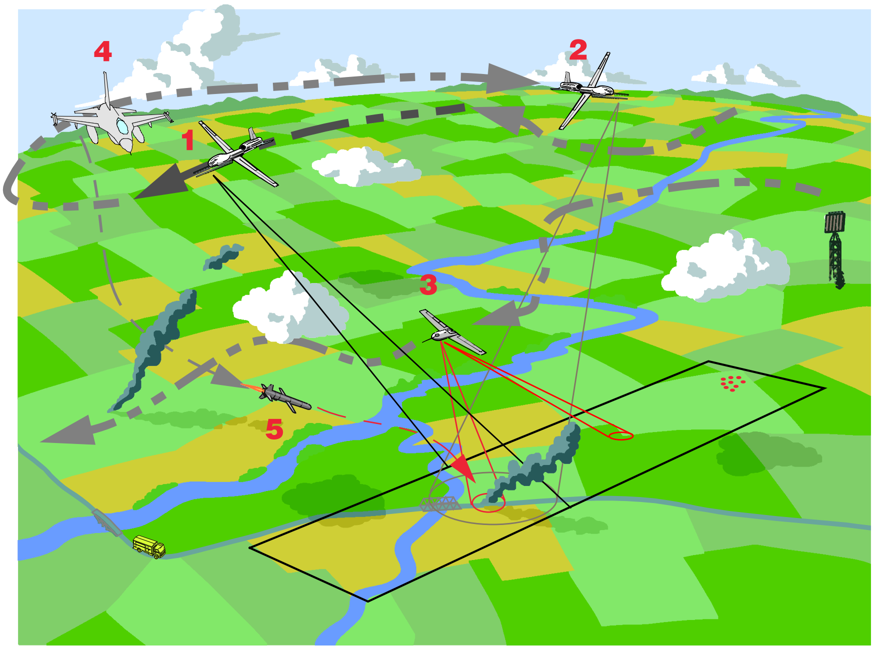


Figure 5.1: A typical military ground surveillance scenario.

This scenario starts with some kind of indication of activity in a specific area. The indication may come in the form of an intelligence report. The actions are then:

- a high-altitude UAV with a SAR sensor are planned to survey the area using stripmap mode. Also, an low-altitude UAV with an IR sensor is pre-allocated to support the operation as well as an UAV with an air-launchable acoustic sensor network on-board. A long-range air surveillance radar is also alerted of the planned activity to follow up the operation.
- The SAR sensor in the first UAV detects many possible targets in stripmap-mode (1). During the data collection phase there are

constraints on the UAV's flight path. In the signal processing step the SAR image is compared with a reference image collected a month ago. This process reduces the target list considerably.

- It is decided that the same SAR should use a spot-mode to resolve suspicious targets (2) and reduce the list further.
- Still we do not know enough about those potential targets since we need a higher confidence level. Therefore we use the pre-allocated low-altitude UAV in stand-by mode. The UAV is ordered to do precision measurement for positioning and ID (3). As can be imagined, the capacity is limited to a few potential targets due to the short available time.
- Finally we reach enough confidence that this is a target worthy of a missile. At this moment it is also decided that it is important with a proper assessment of the coming missile attack. Therefore, the third UAV with the acoustical sensors is ordered to launch a small network of such sensors in the forward estimated path of the target. Meanwhile, the second UAV is following the target. This is done on as long range as possible to minimize detection of the UAV and the threat against it.
- An aircraft launches the missile (4) from relative long range and in an unexpected direction, and hits the target (5) with the aid of the continuously updated information from the optical sensor.
- The acoustic sensors detect the hit, but can also inform us that there are survivors from the hit. In addition, the complete operation have been followed by the air surveillance radar and confirmations have been sent to an operator.

The focus for the sensor control project in this scenario is the planning of, and the methodology behind, each of the many and complex decisions that have to be taken during similar situations as well as the timing of all events.

5.2 A civilian scenario

In the automotive sector, multisensor systems and sensor fusion is currently being introduced. Application examples are collision avoidance, collision mitigation, pedestrian detection, cruise control and automatic brake take-over. Examples of sensor types used are IR-based sensors, radars, cameras and laser scanners. Common processes are detection, classification, image processing, object association and tracking. The fusion system may be weak or strong, the latter by which means that collected information is being used for further sensor control.

Sensor control may improve the adaptability of the sensor fusion systems. This is required for example in order to:

- Apply sensor suites to target detection and tracking depending on weather and daylight.
- Apply sensor suite to target detection and tracking depending on traffic conditions, environment, driver style and road conditions.
- Apply sensor suite to target detection and tracking depending on available information on the car.

6. Conclusions and future work

As previously described the business of sensor control is very complex and is currently lacking an unifying theory or a model. We have in this report pointed at embryos to this, but we have a long way to go before a theoretical framework exists. A theory or a model is necessary to analyse or fully understand this kind of functionality. We have used a vertical approach here to try to see the complete picture or at least a good picture of it. It is possible to identify functionality in the C^3I-system through all levels that have impact on the sensor usage or can benefit from a more close control of the sensor resources.

In order to continue with this kind of work we will use the military ground surveillance scenario described previously as a background for further studies. It is important to have this kind of scenario to make further studies concrete enough to be relevant in the coming years. We will concentrate on specific work packages and about 2 years from now we have as a goal to illustrate some effects of sensor control in a ground surveillance situation. An illustration is a mixture of theoretical studies, simulation and some animation, and presentation techniques to give a good view of the capabilities and drawbacks of sensor control.

The specific areas that we intend to focus on are

- Modelling, including some theory and analyses of the methods based on notation in Appendix C.
- Multi time-scale planning, including aspects of autonomous platforms and resource allocation.
- Conflict resolution techniques. This will also include distributed systems and multiagent techniques.
- A more in-depth analyse of the sensor resource and constraints on its usage.

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Appendix A. An illustration of resource allocation

Step 0: Owner A and B report to the Broker that their respective sensor platform is available

Step 1: The customer, Officer 1 is contacting the broker with a request about surveillance of a ground area

Step 2: The broker knows that UAV-A and UAV-B is in the vicinity. UAV-A have a SAR-radar and UAV-B a IR-sensor. He choose X as a task manager and assign him the UAV:s

Step 3: The task manager X negotiate with owner-A about usage of UAV-A. He get's permission to use it 10 minutes later., and UAV-B is negotiated with owner-B to be put in stand-by for the follow-up task. This is reported to Officer 1.

Step 4: UAV-A is ordered to execute the task and report to the Officer 1 and the common databasen

Step 5: UAV-A execute his task and report according to order

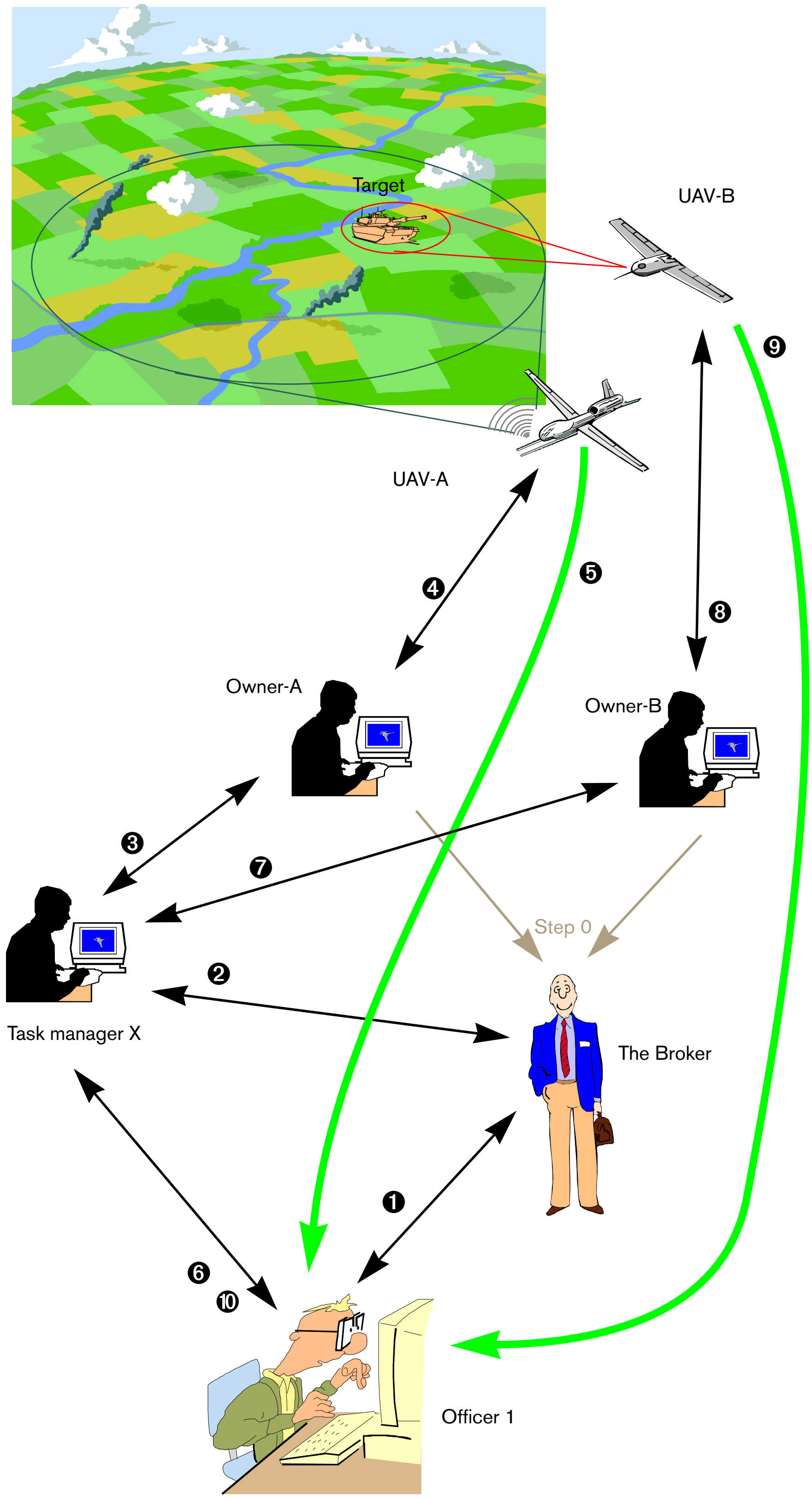
Step 6: Officer 1 analyzes the result from UAV-A and find out that he need more detailed information of a possible target. He contact the task manager X and ask him to fulfil his need.

Step 7: Task manager X negotiate with owner-B about usage of UAV-B.

Step 8: UAV-B is ordered to execute the measurement task and report to Officer 1.

Step 9: The task is executed. The result is reported to Officer 1 and the common database.

Step 10: Officer 1 is satisfied and finish the task.



Appendix B. Theory for distribution of sensor tasks

We have a set of tasks Q_t which should be handled by a network of sensors S, and each task is at every time t processed by exactly one sensor. Let the system of sensors be able to transfer one task from a specific sensor to another in the arbitrary short time interval $[t_0, t_1]$. Q_t is the total set of tasks at the time t and is often written Q.

Look at a certain task q. The utility u gained if the sensor s is processing task q can be described by a function

$$u_{qs}(t) = f(method_{qs}, priority_{qs}, security_{qs}, scenario_{qs}, t) \qquad 0 \le u_{qs}(t) \le 1 \qquad \text{(B-1)}$$

where the argument $method_{qs}$ is method to use for executing q at s, $priority_{qs}$ is the readiness that s gives to q and $security_{qs}$ is security (and counter measures) against vulnerabilities like jamming, destruction etc. Methods to estimate the utility $u_{qs}(t)$ has been described elsewhere e.g. [32], and might sometimes be simplified by heuristic rules for specific classes of tasks and scenarios. Utility is a FOM (Figure Of Measure).

The cost c for this processing is described by a function

$$c_{qs}(t) = g(cru_{qs}, resneed_{qs}, constraints, vulner_{qs}, scenario_{qs}, t) \qquad c_{qs}(t) \ge 0 \qquad \text{(B-2)}$$

where *cru* denotes current resource usage, *resneed* new resources needed, *constraints* is a sensor constraint set and *vulner* denotes vulnerabilities.

The sensor constraint set is introduced as an instrument to express the bulk of heuristic rules. As a first classification, constraints may be of physical and tactical nature. The cost to violate a physical constraint is infinitely large while the cost to violate a tactical constraint is lower. Some general constraints will be given later.

Let

$$r_{qs} = u_{qs}/c_{qs} \qquad 0 \le u_{qs}(t) \le 1 \qquad \text{(B-3)}$$

be the efficiency value of executing task q in sensor s.

At every time point t maximum efficiency e is obtained if the sensor S executes the task q that maximizes the efficiency value, in other words

$$e_S = \arg_q(\max(r_{qS})) \qquad \text{(B-4)}$$

However, if this was the rule several sensors might decide to run the same task. Seen from the viewpoint of a certain task Q, the maximum efficiency e is obtained if the task is executed by the sensor s that maximizes the efficiency value

$$e_Q = \arg_s(\max(r_{Qs})) \qquad \text{(B-5)}$$

In general, we may establish a matrix of efficiency values where each element (s, q) states the efficiency of sensor s running task q. Finding the optimal combination of line-column pairs is analogical to solving an association problem. The Primal-dual association algorithm [31] states a globally optimal solution for this type of problems.

Now, three facts complicates the situation. First, the execution of a task generally persists for a time interval with length greater than zero. Secondly, the achievement of a task often requires work (or sub tasks) in several sensors, in which these sub tasks are to be executed sequentially or in parallel. Thirdly, some sensors might momentarily execute more than one task.

To increase the ability to reason about time, we introduce the notion of time interval. Let $tival$ denote a certain time interval, and let $TIVAL$ be the set of all time intervals, regardless of length. Describe he cost of using sensor s for task q in time interval $tival$ as $c_{s,q}(tival)$, and the corresponding utility as $u_{s,q}(tival)$.

Denote by S_q a sequence of sensors to apply for task q. This sequence is described by $\{s^q{}_{j_1}, s^q{}_{j_2}, s^q{}_{j_3}, \ldots\}$, where j_i is a link number in the sensor sequence and $s^q{}_{j_i}$ is a sensor in the sensor sequence used for task q. The time interval for sensor s running task q is denoted $tival_{s,q}$. The total cost for running the task is then $c_q = \sum_{j=1}^{S_q} c_{s^q{}_{j},q}(tival_{s^q_j,q})$ where the sum contains exactly the sensors in the sequence S_q. Likewise, the utility of the task is $u_q = \sum_{j=1}^{S_q} u_{s_j,q}(tival_{s_j,q})$, and the efficiency follows from (B-3).

The case with tasks doing sensor sequencing requires a more sophisticated method for finding the optimal distribution of sub tasks on S. It is turned into a scheduling problem. In workshop scheduling a similar problem exists. Two strategies may be applied:

(i) Decide sensor and schedule next sub task after termination of the previous one.

(ii) Plan a sequence of sub tasks for each task in advance. This is a very complex problem.

Our goal is to maximize the efficiency, which means that we have to find the distribution that maximizes the efficiency. This is a large optimization problem that can be solved by dynamic programming but this is an inefficient method as many distribution possibilities has to be investigated. Therefore heuristic methods, rules or constraints are needed which also take into account that in practice you can't move a task to so many alternative sensors.

Below is an example set of sensor constraints.

(i) A sensor must not be overloaded. This applies also if a sensor may execute more than one task simultaneously. Assume that, for every time interval, each task at most requires a certain part of a sensor. Let the required usage of sensor s for a task q during the time interval $tival$ be a scalar value denoted by $a_{s,q,tival}$. Then $a_{s,q,tival}$ has a value in [0, 1]. Let $tival$ be a time interval during which a constant set of tasks is executed at each sensor. Then a constraint on the usage of each sensor s is that $\forall(tival \in TIVAL)\left(\sum_{i=1}^{Q} a_{s,q_i,tival}\right) \leq 1$.

(ii) Active sensors should not be used in tasks requiring signal silence (stealth behaviour). Let s_{active} denote the class of active sensors (including radars), and let $q_{stealth}$ denote the class of tasks requiring stealth behaviour. Then the following constraint applies, $\forall((s \in s_{active}),(q \in q_{stealth})) \cdot a_{s,q,True} = 0$ where $a_{s,q,True}$ designates usage of sensor s for task q at any time interval.

B.1 Distribution of tasks over sensor groups within the network

If we have several sensor platforms that cooperate in the network the possibilities for tactical usage will increase. Tasks and roles for the participants in a platform group can be distributed and redistributed at uneven times - to confuse the opposition. Examples of tasks are surveillance, electronic warfare, command and control, communication and navigation.

A way to accomplish a stealthy behaviour of active sensor platforms in a group is to distribute transmit and receive tasks within the group in such a way that each sensor platform does the choice, cueing and combat of their own target without illuminating it with its own active sensor. All active illumination is done for the benefit of someone else within the group. Frequencies as well as target and task distributions can be changed from time to time to further confuse the opposition.

Other possible ways to be stealthy are to distribute the use of passive sensors or passive modes within the sensors so that they complement each other and are able to estimate the required information about the opposition.

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Appendix C. Sensor management. A theoretical framework.

C.1 Foreword.

This paper is written within a project entitled *Sensor Control in Network Centric Warfare, Problem description and important areas.*

The first phase of this project has i.e. the following goals:

(i) define which part of the sensor management domain the project shall concentrate on,

(ii) establish contacts with researchers within universities and high-schools

(iii) analyse the properties of sensors with respect to the possibility of allocation and management

(iv) start to develop a theoretical framework and analytical methods for sensor management

(v) establish one ore two scenarios in order to show the usefulness of sensor management.

This paper deals with point (iv) above, that is the development of a theoretical framework for sensor management.

C.2 Introduction

The purpose of this report is to present a conceptual model for decision making under uncertainty. The reason for this is simply that the environment within which sensor control is taking place is full of uncertainties, and therefore it seems appropriate to base an analysis of sensor control and sensor management on a more general framework for decision making under uncertainties.

There is much useful theoretical literature dealing with decision making under uncertainty. Here we just mention two references namely the books “Decision making under uncertainty, Models and Choices” by C Holloway, and “Causality, Models, Reasoning and Inference” by J Pearl. (See [34] and [35]). A very useful paper on sensor management is the paper by Xiong and Svensson (see [36]).

In spite of the existence of all the literature, we believe that the framework we describe below can be a useful complement to existing literature and hopefully the concepts and notions that we present can be useful whenever one deals with any kind of sensor management problem.

In the report we actually describe two models. In the first we assume that the number of actors within the organisation in charge of the decision making process, is only one, and in the second model we allow for several actors.

The models we present, are build up by subparts, which we call *modules*. Within each module there are “things” that shall be done. The modules are connected. Sometimes there is a definite order between modules, sometimes two or more modules are intertwined.

The plan of the report is as follows. In section C.3 we describe, without much comments, a model for decision making under uncertainty in which we only have one decision maker - one actor. In section C.4 we discuss the model and the modules introduced in section C.3. In section C.5 we generalize the model in section C.3 to a model in which we have several actors - decision makers - who at a final stage must coordinate there actions. In section C.6 we describe *a model for duels* derived by Grahn (see section 3.1 in this report). This model consists of five phases. In section C.7 and C.8 we consider the first two of these phases and relate them to the model for decision making we introduced in section C.3. In section C.9 we describe a *framework for information assessment* based on the report [33] by Bengtsson et al. In sections C.10 and C.11 we discuss the last three phases of the duel model, in section C.12 we make some concluding remarks, and in section C.13 we have made a list of literature which might be of interest for sensor control and sensor management.

C.3 A model for decision making under uncertainty

Decision making under uncertainty is what man does everyday all over the world. There are probably hundreds of scientific books written on this subject, books discussing probability and stochastic models, books discussing preferences, books discussing utilities and cost-benefit analysis, books discussing man's psychology, et.

In this section we shall give a very basic model of decision making under uncertainty which we believe can be used as a basic reference model.

The model consists of a rather small number of modules. The first module, which we picture as the top module, is called the *purpose*. Decisions are related to goals which are related to purposes. Purposes are often implicit and sometimes not articulated at all. One can perhaps say that a purpose answers a question that asks *why* we shall do something.

Our next module is a module called *goal*. Also goals can be rather vaguely formulated if formulated at all. However in the decision making process it is important that one tries to describe the goal - or goals - rather precisely. Just as a purpose answers a question about why we shall do something, a goal answers a question regarding *what* we shall do.

For later reference let us call the uncertainty related to the vagueness of the goal formulation the "goal-uncertainty".

The next module in our model is what we call the *action space*. This module could also be called *action possibilities, decision space* or simply *options*. Sometimes the number of options available are very small. In fact, the number of options might only be two - to act or not to act. A decision to choose a specific action can be seen as an answer to a question about *how* we shall reach our goal.

Sometimes there may instead be a whole spectrum of action alternatives. Note also that even when there are only two actions to choose among, there might be a time variable involved which enlarges the action space substantially.

The fourth module in our general model is a module we call the *state variables*, and the fifth module is called the *estimation of state variables*.

In the module called *state variables* we simply try to identify all quantities - variables, parameters, - of relevance for our decision problem. The contents of this module is quite dynamic, and can both be enlarged and decreased as time passes.

The fifth module - estimation of state variables - is based on the modelling done in the fourth module. In the fifth module one associates numbers (values) to the state variables defined in the fourth module. In this module one should also try to *quantify the degree of certainty* by which the values of the state variables are determined. Some values of state variables can be pure guesses - wishful thinking - some can be extremely precise, due to superb intelligence operations.

The fourth and fifth modules are often strongly intertwined. The state variables chosen in the fourth module are often those that can be estimated, or measured, in some way.

The sixth module is called *consequence analyses*. In this module we try to analyse how the state variables determined in module four, and estimated in module five, will change for each action in the action space. Just as it may be very difficult to determine the true values of the state variables (module five), in general it may be very difficult, indeed, to determine the "true" consequences of different actions.

The uncertainties in the estimates obtained when analysing the different actions, can be due to uncertainties in the input variables. Sometimes the process which is induced by an action is chaotic in nature, which implies, among other things, that its trajectory is very sensitive to input values and therefore the consequences of an action may be hard to predict even if the estimated state variables are very precise and correct.

The seventh module is called *consequence assessments* in which we try to evaluate, assess, the consequences of different hypotethical actions. To perform consequence assessments is also quite difficult but for other reasons than before. Often it is necessary to define *assessment variables*. These variables can take values which are qualitative in nature, (good, bad, very good, etc.), or quantitative to a certain level of resolution. When several people are involved in the decision, - people with different background -, finding assessment variables that all can agree upon as useful and relevant for the problem at hand, is often not easy. If one could agree upon one *grand utility function* by which consequences of all actions can be judged, the underlying decision problem would become rather easy but such a function is seldom to be find.

After one has done the consequence assessments for different actions one has to compare the consequences for different actions. This process is also put in a module which we simply call *decision making*. For this module some kind of cost-benefit analysis is needed. Of course this module is closely linked to the previous module in which we make the consequence assessments.

Sometimes it turns out the uncertainties, are too severe for making a decision. One may then decide to postpone the decision until further information is obtained.

Therefore we have an ninth module called *More information?*. If the answer is no, we enter the last module of our model namely a module simply called *decision* in which we decide which action to take.

If instead the answer to the question “More Information?” is yes, a rather complicated process starts in order to decide what kind of extra information is needed. In this module an important issue is to decide the value of new information. We now quote [34], chapter 14. “What is the value of information in a particular setting? The basic principle is that *information only has value in a decision problem if it results in a change in some action to be taken by a decision maker*. Even though some data or statements from an expert provide new knowledge, it may not have any value in the context of a particular decision problem”.

This definition by Holloway agrees essentially with the definition in the paper [33] where the value of information was defined as the degree by which a decision can be improved.

In order to decide whether certain sensors should be used for information gathering, it is thus necessary to evaluate the effects that new information will have on the assessments of the different consequences of the possible actions. How this shall be done is a problem which is in the heart of this project.

The following figure summarizes the model described above.

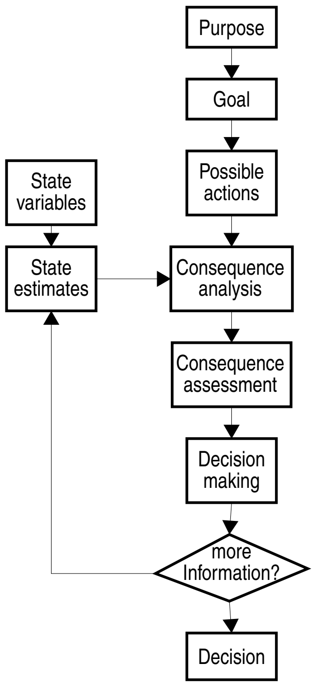

Figure 7.1: Conceptual model for decision making under uncertainties.

Before ending this section we want to emphasize that decision making is often hierarchical in nature. Before making a certain decision on a high level several decisions on lower levels may be needed, and vice versa - before decisions on a lower level can be made, decisions on a higher level might be needed.

C.4 Analyzing the model for decision making under uncertainty

In this section we shall discuss the different modules we have introduced in our model for decision making under uncertainties somewhat further.

As pointed out above the *purpose module* and the *goal module* are related. However it is not unusual that the question of what the purpose of reaching a goal is, is never raised. The goal itself becomes the purpose. What reaching the goal will have for implications is not analysed. The goal is usually concrete and quantitative in nature whereas a purpose often is often qualitative in nature.

Although a goal is often more clearly specified than a purpose one should be aware of the fact that sometimes the goal is also rather unclearly defined, if defined at all. For example the goal of an organisation can be perceived quite differently for different people in an organisation. Sometimes a goal can be described in terms of a numerical function, other times one deliberately uses qualitative expressions in order to define a goal.

Sometimes it is also quite difficult to define when a goal is reached. It is difficult to find state variables or assessment variables that can be used in order to decide the degree by which a goal is reached.

On the other hand even when the goal is vaguely formulated or not formulated at all, when it comes to comparing decisions it is probably so that in many cases people can agree that one decision is better than another in spite of the fact that there is no specific quantity by which one can relate the estimated consequences of different hypothetical actions.

The *action space* can probably often be well specified. Often there are some constraints that may limit the set of possible actions, constraints that can be formulated in terms of monetary costs, in terms of other resources, in terms of behaviour rules, or in terms of political statements.

One uncertainty in this module is due to the simple fact that one has not found all actions available. One has not been *sufficiently creative.*

The action space can sometimes be very large which induces a complexity problem for the decision maker.

When dealing with sensors, say for example an infrared camera placed in an UAV, which one wants to use for surveillance of a certain area, then the action space can be chosen as the set of all flight paths. When deciding which action to take one cannot in this case investigate the consequences for each flight path, since the action space is too large. What one can hope for is a flight path which the people involved in the decision can agree upon is a rationale decision. Such a rationale decision can be obtained by finding a flight path which is optimal in some sense, a sense which people find adequate.

There is always a risk involved when one chooses an action which optimize a certain objective function. The risk is due to the fact that the objective function does not capture all factors relevant to the decision problem at hand. For example if an UAV flies within range from certain weapons, it may be necessary to take into account the risk for being shot down. By using an objective function in which this risk is not included in the objective function this might lead to a flight track for which the risk of being shot down is high. A flight track from which one still can obtain useful information but for which the risk for being shot down is diminished may be a track to prefer. Exactly how the balance between information need and the risk for being shot down shall be made is difficult to decide but it is conceivable that certain rule of thumbs can be found, or that one can find an objective function which has integrated the risk for being discovered and the risk for being shot down.

The module which we call the *state variables* is probably the most important one since it is in this module that we define those state variables by which we want to describe the problem at hand. It is here we determine which factors are the essential ones, its here we make a large number of assumptions regarding the stability, the stationary of state variables surrounding the problem, and assumptions that are necessary to make in order to avoid a too complex description of the world “surrounding” the problem at hand. Some very basic state variables are those state variables that describe the various resources that are available, since these variables often are so called limiting factors.

The work necessary in the module called *estimated state* is fairly straight forward to do, and is often based on practical experiments.

Moreover, as mentioned above, it can also be wise to try to describe the precision of an estimated state variable. One way to do this is to *attach* another variable - or a vector - by which the quality of the estimated value of a state variable is described. For example, in order to describe the precision of a localization parameter one may use a covariance matrix.

In agreement with the theory presented in [33] we call such a variable an *evaluation parameter* or an *assessment parameter*. Note that one can also attach an assessment parameter to an assessment parameter, if that seems necessary.

The module called consequence analysis can be extremely difficult to implement. Sometimes it is simply impossible to say what will happen, i.e. to say with precision how the values of the relevant state variables will change due to different actions. There are simply too many uncertainties, causing a lot of uncertainty in the predictions of the state variables.

One question that arises is how to describe the uncertainties in the predictions. One approach is to introduce distribution functions for each state variable and then try to describe the consequences of an action by a transformation of the distribution functions describing the state variables. The information contained in a distribution function can though be rather difficult to apprehend and comprehend, whereas quantities as mean values and covariance matrices which may be easier to understand. These latter quantities can be determined from the distribution function, if necessary by Monte Carlo simulations.

Another way to handle uncertainties regarding the precision is to describe consequences in terms of sentences such as “in most cases the state variable will take a value at least 5”. Here the exact value of a state variable is not known, but its true value is bounded from below with high certainty.

The module called consequence assessment is probably a module which is often overlooked in practice, overlooked in the sense that little thought is given to the choice of assessment variables. The situation is often such that the creator of a technical tool has another background - comes from another educational culture - than the person that shall use the tool. The performance parameters that are natural for the producer may be quite different from those that seem natural to choose for the user. Therefore one should be thorough and careful when determining the set of assessment variables so that the decision makers have quantities and ordinal numbers to compare, which they feel comfortable with.

The next module we introduced was the *decision making* module. The conceptual idea is that it is in this module the actual comparison between the evaluations of different actions is performed.

It may turn out that some of the important assessment variables on which one would like to base one's decision has no value at all or have very uncertain values, due to lack of information regarding the values of certain state variables. The question that then arises is whether one should try to obtain more information about one or more state variables by information gathering. This is an important question which we shall come back to.

Suppose now we do have to make a decision. How is this to be done? Here one should perhaps distinguish between the situation when a person - or a group of persons - shall make the decision, or if the decision shall be made automatically. In the former case, the case when the decision is to be made by a person or a group of person, then the final decision is usually based on some decision criteria, criteria which in fact may be both intuitive and unarticulated. When instead the decision shall be made automatically as often is the case in sensor control situations since time is a limiting factor, some kind of decision-rule has to be defined and implemented as software. For transparently reasons such a decision rule ought to be based on a fairly small number of well chosen assessment variables.

A rather new technique within computer science is the use of so called *agents*, and *mobile agents*. They may enter as tools at several places in the model discussed above.

C.5 A model for decision making under uncertainty with several actors

A model tries to describe some essential parts of the world for some purpose. The purpose of the model for decision making under uncertainty that we have introduced above is mainly to give some structure to the process of decision making under uncertainties, but also to emphasize the need for relevant assessment variables as a basis for the final step in the decision procedure. However in order to prepare for a situation where the underlying organisation within which the decision making process is taking place, is an organisation with a structure consisting of several rather autonomous units, all of which may ask for sensor resources, it may be useful to enlarge the model described above somewhat. We name this enlarged model *a model for decision making under uncertainty with several independent actors*.

The structure of this larger model is very similar to our previous model. We start again with two modules called *purpose* and *goal*. As we pointed out in section 3 both the purpose module and the goal module can be rather vague at first, and it is often necessary to transfer a generally expressed goal to more concrete subgoals before some actions possibilities can even be defined.

We next introduce a set of modules called *actors* each of which identifies a specific actor - unit - within the organisation. We call each of these modules a *local actor*.

The next set of modules are a set of modules called *local goals*, each of these is associated to a specific actor within the organisation.

Next we introduce a set of modules called *local action possibilities*, a set of modules called *local state variables*, a set of modules called *local state estimates*, a set of modules called *local consequence analysis*, and a set of modules called *local consequence assessment.*

Regarding the modules called *local consequence analysis* and the modules called *local consequence assessment* one has to be cautious, since actions (local actions) performed by other actors within the organisation may strongly influence the outcomes of actions (local actions) taken by other actors. There may be an interrelationship regarding the consequences due to actions taken by different actors. In the modelling, action possibilities of other actors, in case they have influence on one's own local state variables, can be included as state variables in one's own set of local state variables.

Another way to handle this is simply to introduce some further modules in which all relevant variables are included. Therefore along side the set of modules called *local action possibilities*, *local state variables*, *local state estimates*, *local consequence analysis*, *local consequence assessment*, respectively, we introduce five modules called *overall action possibilities, overall state variables*, *overall state estimates*, *global consequence analysis* and *global consequence evaluation.*

Now to the rest of the modules within the framework. “Below” the set of modules called *local consequence assessment* we introduce a set of modules called *local decision making* in which each actor compares and evaluates the consequence assessments obtained when varying the actions in the module *local action possibilities.*

Parallel to these we introduce a module called *global decision making* in which one makes a comparison between all the assessments obtained in the analysis.

The discovery of a need for more observations, more information, may arise in any of the decision making modules. To which actor or actors the resources available shall be given, is based on the assessments made in the module called global decision making. The analysis preceding this decision may be very difficult and requires some estimates concerning the improvement of the consequence analyses and consequent assessments. It is exactly here that the basis for the sensor distribution is laid. And it is in order to handle this module that one may need to find suitable methods by which to compare and assess possible consequences of various actions.

Finally we introduce a set of modules called *local decisions* each of which is associated to a local actor, and a module called *global decision* in which one decides upon one of the actions among the available in the module *overall action possibilities.*

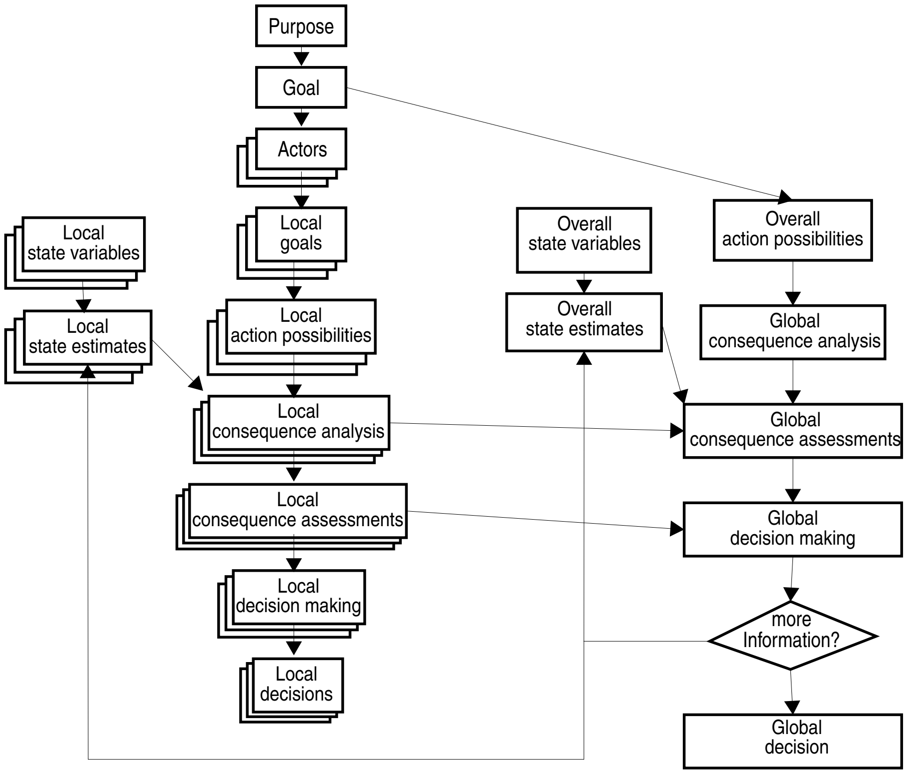

Figure 7.2: Conceptual model for decision making under uncertainties with several actors.

C.6 A model for the duel

In this section we shall discuss a conceptual model that introduces and defines different phases in a duel situation. (See Grahn, section 3.1 on page 27) The reason for discussing this model is that we want to relate this model to the model for decision making introduced above. The phases of the duel model according to Grahn are

- (i) the environment phase
- (ii) the decision phase (to act or not to act)
- (iii) the selection phase (which sensor, which platform, which weapon to choose),
- (iv) the “acting” phase
- (v) the evaluation phase.

Each of these phases has a certain spread on the time axis. Often the time intervals for the decision phase and the selection phase is short. One has to make a quick decision whether to act or not to act, and quickly decide how to act. Sometimes these two decisions are intertwined - when we make the decision to act we already have an idea of how to act. Sometimes though, this is not the case, and we are genuinely uncertain of how to act.

In this, and the following sections, we shall discuss the different phases introduced above, and place this model for duel into the framework for decision making under uncertainties we have discussed in earlier sections.

C.7 The environment phase.

We picture the world as being in some kind of rather steady state. We have assignments, we have goals, there are actual threats (confirmed threats), and there are possible but yet unconfirmed threats. Assignments can be performed individually or in cooperation.

Often the present state situation has been obtained “organically”, by which we mean that he present situation has been obtained by small changes throughout time. There are certain rather well-defined goals to fulfil, which in essence have to be the same for some time.For this reason the *resources* available - - resources in equipment and personal - are often adjusted to these goals, and to the estimated state of the surrounded environment. It is when the environment (the outer world) changes rapidly, that there may arise conflicts among our own leaders (political, civilian and/or military leaders) regarding how best to use the limited resources available. If the resources available e.g are for protection of Swedish territory the resources are often closely linked to our view of the present political situation, and our prediction of the political situation in the near future.

If we consider the duel situation within a Nordic Battle Group scenario the amount of resources for information gathering will most certainly often be insufficient, and therefore, in this situation careful analysis of how to best use sensor equipment is of great importance.

In order to formalise the situation let us start by introducing the letter R to denote our *resources*. By $R(t)$ we denote our resources at time t, and if we write $R = (r_1, r_2, \ldots, r_M)$ we regard are resource R as a vector where each component represents the amount of a certain kind of resource. R will from now on be called the *resource vector*.

For example, suppose that our goal is to have surveillance of the Swedish boarder. The different kind of resources at our disposal can then be, radars, aeroplanes in the air, aeroplanes on the ground, ships, vessels, submarines, - in port or at sea -, et. The resource vector R can contain a various number of components depending on the problem at hand.

The values of the components of the resource vector depend among other things on our estimation of how much resources are needed to fulfil the goal. This estimation is often based on an analysis of other organisations plans and intents, and since it can be difficult to find out the intentions of other organisations our estimations of how much resources are needed can be wrong. Also, since the creation of specific resources can cost money, the resource vector of course also depends on how much money is available.

The resource vector depends also on our estimates of possible *threats*. Threats can be well-established with little uncertainty, or threats can be more uncertain, they can exist in present time or occur in future time.

We shall now introduce some notations regarding threats. We simply let H denote the set of possible threats, where a threat shall be considered as being on a rather high - general - level. The Swedish word we have in mind is “hotbild”. We denote the elements in the set Ɨse of threats by $H_1, H_2, \ldots$.

Starting with a certain threat H in the threat set Ɨse, we then try to identify possible actions and activities by the enemy associated to this threat H. The set of all conceivable hostile actions and activities will be denoted β and a specific hostile activity will be denoted b or b_i if we want it labelled, or b_i^H in case we want to emphasize that it is linked to a specific threat H.

To be somewhat more concrete, let us for sake of discussion, assume that our task is to do surveillance of the Swedish boarder. In the neighbourhood of the Swedish boarder most of the time various activities are taking place. Often and rather regularly aeroplanes from foreign countries enter Swedish air space. Our surveillance resources are adjusted so that they can handle such incidents if 1) they do not occur too often in the long run, and 2) there are not too many incidents at the same time. In the steady state situation we do expect a certain number of overflights or near overflights of the Swedish boarder, and usually we do not consider these overflights as signs of preparation of an attack on Sweden.

Interesting problems in this context are for example to try to detect whether there has become a change in the mean frequency of foreign activities along our borders, or to try to detect new kind of activities in our neighbourhood.

Let us end this section by placing what we have done so far into the framework for decision making we have introduced above.

The *purpose* could be defined as “to guard the Swedish boarder”. The *goal* could be “to detect hostile activities and if necessary act upon them”.

We assume that we only have one actor on our own side. The next module in the decision making model is the module *possible actions*. However as we have mentioned above our actions are dependent on the enemies action so in some sense some of our action possibilities are to be seen as *reactions*. Therefore before doing the list of possible actions it might be necessary to do the list of state variables, and also the list of state estimates, where in particular the state variables referring to the state of the enemy are of interest.

We have already introduced one state variable related to the state of the enemy namely the state variable defining the threat situation. The values that this state variable can take namely the values in the set H are rather abstract and general in nature, but definitely come into the picture in the assessment phase.

Other important state variables are variables that describe our resources and also state variables that describe the resources of the enemy. Those resource variables that are “our own” can usually be well estimated whereas the resource variables associated to the enemy often are much less known.

We indicated above that our possible actions depend on the actions of the enemy. This implies that when doing *consequence analysis* we *need not* do all possible combinations of actions and of state values. Regarding the state variables which describe the state of the enemy we often do not know the exact values of these state variables, and therefore have to analyse the consequences of different actions for many different values of these state variables.

In the environmental phase it also seems appropriate to introduce the concepts: *observation parameters* and *observation vectors*, which also can be regarded as state variables. This class of state variables are quite important since they can give information about changes in the environment and other state variables.

C.8 To act or not to act

The starting point of this phase is caused by the discovery of some activity which might lead to a specific hostile action. In order to describe the situation in mathematical terms we again need some notations.

Thus suppose the general threat situation can be described by H. Let b be an activity by the enemy which started at time t_0.

We now introduce two probability distribution functions, namely

(i) $p_d(t;b, R, t_0)$ = the probability that we have detected activity b, which started at time t_0, before time t, given that our resources are R,

(ii) $p_i(t;b, R, t_0)$ = the probability that we have been able to identify activity b, which started at time t_0, before time t, given that our resources are R,

Since it is more difficult to identify an activity than to observe an activity, clearly $p_d(t;b, R, t_0) \geq p_i(t;b, R, t_0)$.

Quantities such as p_d and p_i can be very useful when trying to decide whether to act or not to act. Note however that the quantities do not really exist by themselves but exist only as quantities in a mathematical modelling framework.

Quantities that are strongly related to the two probability functions we just introduced are the following four:

(i) $T_d(b, R, t_0)$ = the time of detection of activity b given that our resources are R and the activity started at time t_0,

(ii) $t_{p_d}(b, p, R, t_0)$ = the first time when the probability that we have detected an activity b that started at time t_0 is larger than p given that our resources are R,

(iii) $T_i(b, R, t_0)$ = the first time that we can identify the activity p with certainty, given that our resources are R and the activity started at time t_0,

(iv) $t_{p_i}(b, p, R, t_0)$ = the first time the probability that we have identified an activity b that started at time t_0 is larger than p given that our resources are R,

The quantities T_d and T_i are in principal *random* quantities, and are quantities that one can introduce without explicitly defining their distribution functions.

Once one has introduced distribution functions associated to the quantities T_d and T_i one has modelled T_d and T_i as ordinary stochastic variables.

In contrast to T_d and T_i the quantities p_d, p_i, t_{p_d} and t_{p_i} are quantities that require some kind of mathematical modelling to make sense. In fact once one has defined the two probability distribution functions p_d and p_i, we have at the same time defined the probability distribution functions of T_d and T_i since

$$F_{T_d}(t) = P_r(T_d < t) = p_d(t;b, R, t_0)$$

and

$$F_{T_i}(t) = P_r(T_i < t) = p_i(t;b, R, t_0).$$

Moreover the relation between p_d, T_d and t_{p_d} is given by
$t_{p_d}(p) = \min\{s \ni P_r(T_d \leq s) \geq p\} = \min\{s \ni p_d(s) \geq p\}$
and the relation between p_i, T_i and t_{p_i} is similarly given by
$t_{p_i}(p) = \min\{s \ni P_r(T_i \leq s) \geq p\} = \min\{s \ni p_i(s) \geq p\}$

All of the quantities we have introduced above can of course be regarded as state variables.

We have here not discussed the rationale behind introducing these particular variables, and it is by no means certain that the ones we have chosen here are the most appropriate. One reason for introducing the state variables T_d and T_i is that the smaller the values $T_d - t_0$ and $T_i - t_0$ are, the longer period will we have for organising our countermeasures. Therefore it seems relevant to introduce the state variables introduced above. The drawback however is that they are difficult to determine with precision.

Another way to start the analysis is to start by defining a set of state variables associated with observations. It is the accuracy of the observations which is a basic factor when determining state estimates of other state variables.

So we see that we enter a classical dilemma. On the one hand we can not do better than what the sensors we have at present can produce. On the other hand when looking into the future we need to identify the most important state variables first and then see if we can find techniques by which we can obtain observations from which we can determine the state estimates of these significant state variables.

Regarding the problem “to act or not to act” one way to handle this problem is by constructing action criteria based on sequences of observation vectors, and whenever a criteria is fulfilled one is obliged to act. Probably, in reality, this “criterion”- method is the one that is most often used, although perhaps the criteria definitions are not 100% specified, but instead often rather intuitive. Thus, when it comes to the question of whether to act or not, one way to handle this question is to define a set of decision criteria,

Sometimes an event is such that it can not be checked against the set of criteria one has created. Thus the situation at hand is basically completely new. However “a new situation” can be a decision criterion in itself, and by introducing such a criterion for when to act one has a set of decision criteria which should cover all situations. The drawback is that the set of new situations can be large and in some of these new situations it can be difficult to decide *what* to do.

How one determines ones set of decision criteria depends on the usual things that are involved in decisions namely things as, our purpose, our goal or our task, the threat situation, our resources, the cost involved in using our resources, the estimated damage obtained if proper action is not taken, etcetera. In short, in order to determine the set of decision criteria, one needs to make several cost-benefit analysis. What are the possible consequences for not acting, and what are the costs and likelihoods for each of these consequences? In order to perform such cost-benefit analysis, usually mathematical modelling is needed.

Before we continue our discussion on Grahn’s model for the duel we shall present some thoughts regarding information evaluation.

C.9 On information evaluation

In this section we shall briefly describe a framework for information evaluation.

One difficulty with information evaluation is that an information object can be extremely valuable when it is new and worthless when it is old. Another difficulty is that the value of an information object is usually very context-dependent. A third difficulty is that an information object is very receiver dependent. An x-ray image is of little value for the patient but can be of great value for a radiologist.

In the paper [33], a framework for information assessment is presented and we give here a brief description of this framework. To an *information object* we associate the notion *information parameter*. To every information object - one associates a number of information parameters. The number of information parameters can both increase and decrease as time passes. Information parameters are divided into three classes, namely: 1) *meta-data parameters,* 2) *content parameters*, and 3) *assessment/evaluation parameters*.

The meta-data parameters give information *about* the information object *itself*. For example: When the information object was created, what type of information it is, who created it etc.

The content parameters give information about the contents of the considered information object. If the information object is a radar image a content parameter could be the number of possible platforms seen in the image.

The assessment/evaluation parameters give some kind of evaluation of either the information object itself or of another information parameter. If there is an information parameter that gives information about the position of a platform, another information parameter - evaluation parameter - can give information about the degree of precision of this location parameter. To express degrees of precision of location one can sometimes use covariance matrices. For other type of information one can use probability estimates as evaluation parameters. An assessment parameter can also be used to give an estimate of the importance of an information object.

These three categories of information parameters are by no means exclusive. One and the same information parameter can be categorised as a metadata parameter, a content parameter or an assessment parameter. For example if an information object is highly classified that piece of information can be regarded as a metadata parameter (information about the information object), it can be considered as part of the contents of the information object and therefore considered as a content parameter and it can be considered as an assessment parameter since it gives indirectly an *importance label* to the information object.

Information parameters are defined when an information object is created, and can be regarded as connected to the information object under consideration.

Sometimes one can only define a relevant information parameter, and not also give a value to this information parameter.

In summary, given an information object we associate a list of information parameters and to each of these information parameters we, if possible, also give a value. In order to handle the information which is extracted from an information object by its information parameters automatically, we need a common list of information parameters and a common list of metric scales, so that a pair *(i,a)* can be interpreted by those who have access to the list and the metric scale, as “information parameter *i* taking the value *a*”.

Information parameters are so to speak defined at the *sender’s side*. We now look at information from the *receiver’s* point of view. At the receiver’s side we assume that a person wants information in order to improve his knowledge before making a decision. We consider a situation when a person has a specific task to fulfil. In preparing for this task the person makes a list of what kind of information and what kind of resources he needs in order to fulfil his task efficiently. When doing this the person might discover that there is some important information that is missing. He/she therefore makes another list: a list of information needs.

The receiver can create an indicator function - a filter function -, based on the list of information needs, and use this list for example when specifying his/her sensor requirements.

C.10 The selection phase

We now return to the duel model of Grahn. As we pointed out above the two questions “*if* one should act or not” and “*how* to act” are closely related.

We are now in the phase when we have to decide how we shall act. We can now model things according to the model for making decisions under uncertainties that we have described above. Thus we assume that we have a goal to achieve. We have certain actions to choose among. We have a model of the environment, described by state variables, and for many of these state variables we have estimations all of which we have gathered together in the module called estimated state.

Suppose now that we have received such information, that indicates that we have to investigate if we shall act, and how we shall act if we decide to act.

To do this analysis we need to make an analysis of what might happen under the various actions we have at our disposal.

This means that we have to do consequence analysis for each action and then do consequence assessments for each action. The better estimate we have regarding our state variables the larger is the likelihood that our analyses of the consequences of various actions are correct. However usually one can not be sure what the outcome of an action will be even if we know the true state exactly. There is always some uncertainty.

Regarding the evaluation of the consequences, one difficulty is due to the fact that we do not know the outcome of an action. Sometimes one can present the consequence analysis by a set of possible outcomes, and to each outcome one can associate a number - a likelihood number, or a probability number. However such numbers are seldom very precise, and one should rather to each possible outcome associate an upper likelihood and a lower likelihood. If the consequence analysis is presented in terms of possible outcomes with probabilities one can then use methods using utility functions in order to find a ranking between possible actions.

In the consequence evaluation module one part of the analysis concerns to what degree the goal we have formulated will be fulfilled under various actions. Some actions may not lead all the way to the goal we have formulated but may instead be cheap.

Another part of the analysis consists of describing the certainty of the results of various actions. Here it would be helpful if one can find good measures of uncertainty which are easy to comprehend.

C.11 The evaluation phase

After the selection phase is completed one has decided how to act. The next phase is then the action phase, and that phase contains little analysis. The last phase is the evaluation phase in which we try to estimate whether our goals have been achieved. This phase is more of an observation phase than an analysis phase.

C.12 Concluding remarks

The main purpose of this report has been to present a general conceptual model for the problem of decision making under uncertainties. This model consists of a number of modules together with a number of notions associated to these modules. The idea is that such a general conceptual model shall simplify the analysis of a concrete decision problem and also simplify the development of algorithms and software implementations.

A secondary purpose has been to test how the conceptual model for duel as is described in section 3.1 on page 27 can be handled within the framework of the model for decision making under uncertainties introduced. So far there does not seem to be any problems to apply the decision making model to the duel model.

C.13 References

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