Interaction between action and motion planning for an agile Earth-observing satellite

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Abstract

In this paper, we underline the complexity of the activity planning problem for an agile Earth-observing satellite, when trying to consider all the real problem aspects. In particular, we show how action planning (which action to choose ?) and motion planning (which movement to make ?) are inextricably linked. We conclude with the algorithms of automated planning we can reasonably use in this context.
Keywords : action planning, motion planning

Physical system

The physical system is an Earth-observing satellite (EOS). As for each Earth-observing mission, it is located on a heliosynchronous and circular low Earth orbit. This orbit is nearly polar, which allows the satellite to take advantage of the Earth rotation to cover the whole Earth surface.

This is a super agile satellite insofar as it can make very fast attitude movements around the three axes (roll, pitch, yaw) thanks to gyroscopic actuators (Chrétien, Llibre, and Jouhaud, 2004). This agility enables it to image a zone on the ground by scanning it and move on to the next one very quickly. Due to this agility, observation of a given ground zone, on a given revolution, can be freely performed within a visibility temporal window (observation angle more or less significant).

Furthermore, this satellite can perform observations day and night thanks to its optical instrument which contains two focal planes : one for observations during daylight (on the ground) in the visible domain, the other for observations during day and night in the infrared domain. It is also equipped with a mass memory to record observation data, a high-rate and multidirectional antenna to download these data towards a ground station, during visibility temporal windows, and solar panels to recharge batteries during daylight (on board).

To make the satellite agility possible, optical instrument, antenna and solar panels are body-mounted. This compels to verify that, for each observation, an attitude movement will actually lead to perform a given observation by scanning the related zone. This compels to verify that, for each attitude movement, the optical instrument is not dazzled by the Sun (in order to avoid the instrument deterioration). This also implies that, when the satellite is visible from a ground station (during visibility windows), downloading activity is possible only if the satellite attitude enables it : the station must be included within the emission cone of the on-board high-rate antenna. Moreover, this implies that the energy produced by a solar panel will depend on the satellite attitude trajectory, since it is a complex function of spacecraft location and orientation.

A minimal duration is necessary to preheat an instrument (a focal plane or the high-rate antenna) in order to use it. The temperature of the visible focal plane, as well as the antenna's one, cannot exceed a maximum value. Due to these temperatures and energy limitations, switching off an instrument between two uses can be necessary. Nevertheless, reliability expectancies lead us to limit the number of *on/off* commutations and the total time during which this instrument is *on*.

Planning system

Usually, a control ground station ensures the management of this kind of satellites. It continually receives observation requests from users and produces, every day and for each satellite, a plan of activities, while trying to meet the demand. Then, the plan is sent to the corresponding satellite for execution on board.

Even though some research has already been performed about more autonomous, reactive and "intelligent" satellites (Chien, Sherwood, and Tran, 2005; Damiani, Verfaillie, and Charmeau, 2005; Beaumet, Verfaillie, and Charmeau, 2009), we are considering this classic management (on-ground planning). Nevertheless, a high number of visibility temporal windows per day enables, here, a frequent communication with the satellite.

Planning problem

Criterion and constraints

Since observation requests mostly overtake the satellite capacities, daily planning is an optimization problem under constraints.

The criterion that needs to be optimized is a complex function, but can be mathematically expressed. This takes into account the performed observations, the priority lent to each of them, their realization quality (acquisition angle, predicted cloud cover), the downloaded images, and the duration between realization of a given observation and data reception.

The constraints that need to be satisfied are related to the considered physical system. For some of them, it is extremely difficult, not to say impossible, to produce a mathematical expression. However, as we are going to explain later, these constraints can be verified by simulation.

State variables

The state variables involved in the physical system model, are the following : current time ; attitude position (actually a vector representing the satellite orientation) and attitude velocities around the three axes ; available energy ; available memory ; state of each instrument (*on* or *off*) ; for each instrument, the number of *on*/*off* cycles and the total time, up to this moment, during which this instrument is switched on ; the temperatures of both the visible focal plane and the high-rate antenna.

Possible actions

The possible actions are the following : performing an orbital maneuver (to maintain the satellite on its reference orbit) ; performing the observation of a ground zone ; downloading data related to an observation ; switching on an instrument (a focal plane or the high-rate antenna) ; pointing the Sun (to recharge batteries) ; pointing the Earth center.

Orbital maneuvers, observations, sun and geo-pointing activities constrain the satellite attitude : to achieve one of these actions or the transition between two of them, a specific attitude trajectory is expected. On the other hand, downloading activities do not affect the satellite attitude, but depend on it (emission cone of the high-rate antenna). Switching *on* or *off* an instrument actually depends on the observations and downloads which are planned.

Therefore, orbital maneuvers, observations, sun-pointings, geo-pointings, and attitude rendez-vous are mutually exclusive : a satellite is executing, at each moment, only one of those activities. However, downloading data or switching on an instrument is done in parallel.

Attitude movements

We currently have algorithms able to check whether or not an attitude rendez-vous is possible between two attitude-constrained actions, and produce a precise attitude trajectory that is feasible.

These algorithms need, as input, a starting attitude, an ending attitude and a duration. They basically determine if there exists a feasible movement

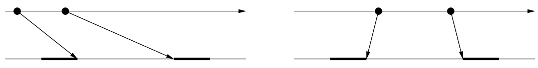

Figure 1: The minimum transition time is variable.

of such a duration between these two attitudes, given the capacities of each gyroscopic actuator. If there is one and if necessary, they generate a feasible attitude trajectory, broken into three phases for each axis : a constant acceleration phase, followed by a constant velocity phase, followed by a constant deceleration phase.

Furthermore, the satellite will often have to reach, as fast as possible, an action's starting attitude, within a fixed window (to quickly move on to a new observation, for instance). It is a difficult problem which looks like a problem of tracking a mobile target from a mobile vehicle. The minimum time for this attitude rendez-vous can be computed with a dichotomic search by calling the same algorithms. An optimal result is obtained under certain conditions : a satellite movement can be decomposed in the three previous phases along each axis ; if an attitude rendez-vous is not possible within a given time, it is not possible within a shorter time.

Once a trajectory is available, it can be simulated step by step. Thus, energy production is estimated, the windows, during which downloads are effectively possible, are computed, and the instrument non-dazzle is verified.

However, those algorithms are not able to compute a minimum transition time between two observations without considering an ending time for the first one. The minimum transition time between the observation o_1 of a ground zone and the observation o_2 of another one depend on these zones, but also on the attitude at the end of o_1 and, therefore, on the realization time of o_1 (see figure 1). For another example, they cannot compute energy production or the effective visibility windows during, first, the transition from o_1 to o_2 and, then, the realization of o_2. This energy and these windows depend on the realization times of both o_1 and o_2. They can only be estimated by simulating the trajectory, which is only possible once the realization times of both o_1 and o_2 are fixed.

Consequences on the modeling task

Action planning usually tries to model the problem within a generic modeling framework, such as integer linear programming (Nemhauser and Wolsey, 1988), constraint programming (Rossi, Beek, and Walsh, 2006), action planning (Ghallab, Nau, and Traverso, 2004) or task scheduling (Baptiste, Pape, and Nuijten, 2001), to use the generic algorithms associated with these frameworks, and solve the problem. Thus, you get a formal model that guaranties feasibility (and sometimes optimality) of the produced plans, depending on the expressed constraints. Moreover, you can call mecanisms of heuristic research, bound computation and constraint propagation which are part of the generic algorithms.

This is, actually, the approach adopted in some previous works dealing with the planning problem for agile (or not) EOS (Bensana, Lemaître, and Verfaillie, 1999; Lemaître et al., 2002). Nevertheless, the planning problems were much simpler : they did not take into account downloads, energy, dazzle, instrument switchings on, and considered agility only in a simplified way.

This approach seems very difficult to apply here, because a precise model is really hard to obtain. Such a model would imply many precomputations for each instance of the planning problem. Here are some examples : for each couple of observations $\langle o_1, o_2 \rangle$ and for each realization time of o_1, computing the earliest starting time of o_2 ; for each couple of observations $\langle o_1, o_2 \rangle$, for each realization time of o_1 and for each realization time of o_2, computing energy production and the effective visibility windows generated by, first, the transition from o_1 to o_2 and, then, the realization of o_2.

Another approach would consist in learning, by intensive simulations and regardless of the problem instance, the parameters of mathematical expressions to get good approximations of the quantities we look for : for example, for each attitude couple $\langle a_1, a_2 \rangle$, for each duration du, for each sun direction and for each station direction, learning the trajectory which enables to transit from a_1 to a_2 within du and without dazzle, as well as the energy production and the effective station visibility windows. We have not explored this method forasmuch as the model to learn looks extremely complex, and approximations do not guaranty feasibility of the produced plans.

In the following section, we show how it is possible, even without getting such a model, to design algorithms that, at least, produce feasible plans.

Planning algorithm

The planning algorithm we are implementing is overall a chronological greedy algorithm : "chronological" since two consecutive decisions are made on two consecutive temporal intervals (on $]t_1, t_2]$ and $]t_2, t_3]$ with $t_1 < t_2 < t_3$), and "greedy" because successive choices are made, in general, without casting doubt on the previous ones. However, a few backtracks will be allowed in case of constraint violations. The algorithm is based on a four level organization of actions :

1. orbital maneuvers and observations ;
2. sun-pointing and geo-pointing activities ;
3. downloading activity ;
4. switchings *on/off* an instrument.

Each decision-making time corresponds to the end of an action of level 1. At this moment, the satellite state is totally known, and a decision is tried to be made between the current time and the end of the next action of level 1 that is accepted. This is a complex hierarchical decision that includes four decision levels (at each level, decisions are made on the related actions).

At the first level, the next action of level 1 (orbital maneuver or observation) and its starting time have to be decided. Typically, priorities and starting times are considered to select this action (the most priority action, or the earliest feasible action so as to leave space for further actions). To make a good trade-off between priority and starting time, we are proposing the following rule : among the most priority actions that are feasible from the decision-making time, select the earliest one, for example a_1 ; among the most priority actions that are feasible before a_1 and do not prevent the realization of a_1, select the earliest one, for example a_2 ; among the most priority actions that are feasible before a_2 and do not prevent the realization of the sequence $[a_2, a_1]$, select the earliest one, for example a_3 ; and so on, until no action is satisfying the conditions. The last inserted action is then accepted as the next action to perform (for example a_3 if no action is feasible before a_3 or if the feasible ones prevent realization of the sequence $[a_3, a_2, a_1]$). At this stage of the algorithm, it is just verified if there exists an attitude trajectory that performs the considered action sequence. Let a be the accepted action. The starting time of a is equal to : the imposed time if this is an orbital maneuver ; else, the earliest time if the realization time of a impacts the realization time of following actions ; else, the moment that best favours realization quality of a (when getting the smallest observation angle).

At the second level, the actions of level 2 to insert before a are chosen. They are accepted only if they are feasible. A sun-pointing is chosen during daylight (on board), whereas a geo-pointing is chosen during night. A pointing of maximal duration is systematically planned (the earliest starting time and the latest ending time). Again, at this stage, it is just verified if there exists an attitude trajectory that performs the considered action sequence. Once the decisions of level 2 are made, the satellite attitude trajectory from the current time to the end of a is known : it is now possible to verify non-dazzle and compute the effective visibility windows for each ground station.

At the third level, the actions of level 3 to insert within the effective visibility windows are chosen. This is a typical *knapsack* problem for which an approximate solution is given by a classic heuristics (ratio between extra gain and volume). At this stage, the verified constraints are those related to the available mass memory and the downloading actions (within effective visibility windows). Once the decisions of levels 1 and 3 are made, the need for instrument activations is known from the

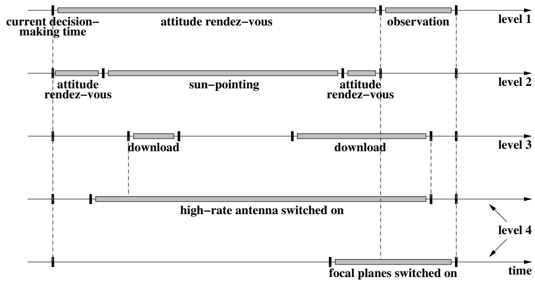

Figure 2: A possible scenario after one decision step.

current time to the end of a.

At the fourth level, actions of level 4 are chosen. To that end, resources are taken into account : energy, temperatures of both the visible focal plane and the high-rate antenna, the number of *on/off* commutations already done for each instrument and the total time when each instrument is *on*. It is also necessary to verify that, if a sun or a geo-pointing is chosen after the end of a, the satellite will be able to reach the end of the next night period (on board) with enough energy.

As soon as the decision process is finished, you get a scenario, feasible by the satellite, from the current time to the end of a (see figure 2 for a possible scenario). Since the satellite state at the end of a is known, a new decision process can be engaged, with the end of a as starting point.

At each decision-making level, it is necessary to define : reasonable decision rules making choices that should satisfy the constraints and optimize the global criterion ; mecanisms verifying the contraints when a decision is made ; mecanisms allowing alternatives when constraints are violated.

Possible improvements

The proposed algorithm appears naive and ineffective compared with other methods, applicable in theory, such as local search, tree search or dynamic programming algorithms. However, we can improve it and make it very effective by following usual techniques : the decision rules used at each level can be as sophisticated as wanted ; these rules can be biased and used within an iterated stochastic greedy search, effective on many problems (Bresina, 1996; Cicirello and Smith, 2005; Pralet and Verfaillie, 2008) ; upper bound computation on the objective value is possible at each step of the greedy algorithm, so that the search can be stopped when the current bound is less than or equal to the best plan value ; long-term learning mecanisms for the rule parameters, inspired by ant colonies (Dorigo, Maniezzo, and Colorni, 1996; Solnon, 2008), could be also envisaged.

Finally, please note that mecanisms based on decision rules can be replaced, at any level, by other mecanisms. For instance, a local search can be used for first level decisions, which are crucial, and greedy searches for the others. But, difficulties could appear (local moves barely possible) . . .

Conclusion

To conclude, we have underlined the complexity of a real-world planning problem in which action and motion planning are inextricably linked. A pragmatic approach is proposed to deal with this specific problem. However, this approach (chronological greedy search that makes decisions in a hierarchical manner and verifies constraints by simulation) may be generalized to handle other situations that involve action and motion planning, such as planning for Universe-observing satellites, fixed-wing UAVS or earth robots.

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