OPTIMAL 6 AXIS COMMAND OF A SPACE VEHICLE WITH A PRECOMPUTED THRUSTER SELECTION CATALOGUE TABLE

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ABSTRACT

An efficient on board algorithm is presented determining the optimal jet selection and firing duration for the 6 degrees of freedom command of a space vehicle controlled by fixed thrusters. This method involves a precomputed fixed catalogue table of jet selection and inverse command matrix data preloaded in the flight software not depending on the center of mass. The method applied for the thrusters command in RV of the Automated Transfer Vehicle (ATV)[1] features a reduced on board power processing demand, a feasible table memory size and nice deterministic characteristics for the vehicle design.

1. INTRODUCTION

The space vehicles ensuring a mission of rendez-vous in space with the role of the chaser must have a fine 6 degrees of freedom manoeuvring capability. They are generally equipped with a set of fixed thrusters of constant thrust commandable by modulated firing pulses that allow the translational and rotational command of the vehicle on all axes. The task of the on board Thruster Management Function (TMF) is to determine the proper jet selection and their firing command duration to realize a force / torque impulse prescribed at each cycle by the Control function of the vehicle.

The capability to command forces and torques with reduced residual coupling effects is a sizing feature for the control accuracy, but presents a difficulty in the case of non axis-symmetric thrusters layout, as the TMF design cannot rely on simplified assumptions on separation between command axes. A new principle of TMF for 6 degree of freedom command is applied to the ATV (Automated Transfer Vehicle) for its Control in Rendez Vous. This algorithm chosen as an alternative to the Simplex algorithm [2] for its deterministic features and reduced processing demand, calculates on board the 6 axis optimal jet combination and firing with the support of a precomputed fixed catalogue table of jet selection and inverse command matrix data preloaded in the flight software. The method applied to the ATV [1](Automated Transfer Vehicle) for its control in Rendez-Vous is presented in the following after an introduction on the propulsive architecture characteristics driving the design of the TMF.

[1] *the ATV is an European Space Agency project , application of this algorithm to ATV is funded by ESA in the frame of the ATV Flight Segment development contract with EADS ST as prime contractor*

2. THE ATV ATTITUDE AND TRANSLATION CONTROL SYSTEM

The Automated Transfer Vehicle (ATV) is an ESA funded project of cargo spacecraft designed for the servicing of the International Space Station (ISS). The ATV ensures its orbital manoeuvres and Rendez Vous thanks to a Guidance, Navigation and Control (GNC) function [1] and to a bi-propellant propulsion system with fixed thrusters.

2.1 The ATV Propulsion System

The propulsion system includes 4 main engines (Orbital Control System) of 490N each for the realization of the major increment of velocity completed by an Attitude and Translation Control System composed of 28 smaller jets (ACS) each one producing about 220N of thrust. The ACS thrusters are used for the attitude control of the vehicle, the realization of small orbital velocity increment ΔV (trim corrections) and for the fine translation control in the RV phase until docking to the ISS. The overall 28 ACS thrusters are distributed on a set of 8 pods as illustrated on figure 1 and 2.

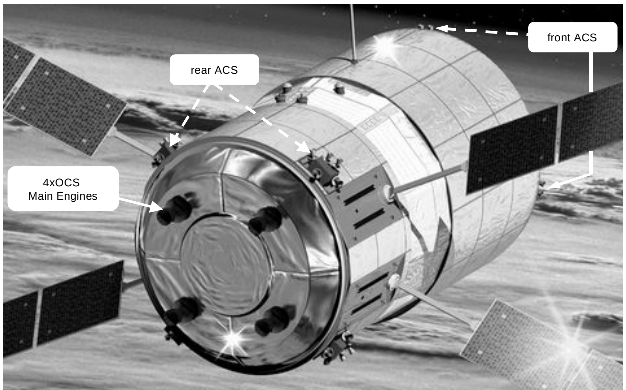

Figure 1 ATV general view and ACS pods locations[2]

[2] *ATV artistic picture by courtesy of ESA*

The figures 2 illustrate the locations orientations of the ACS thrusters. As shown on the figure, the rear thrusters orientation are tilted with respect to the main vehicle symmetry axis in order to minimize the thrusters plume impingement effects on the structure and on the solar arrays .

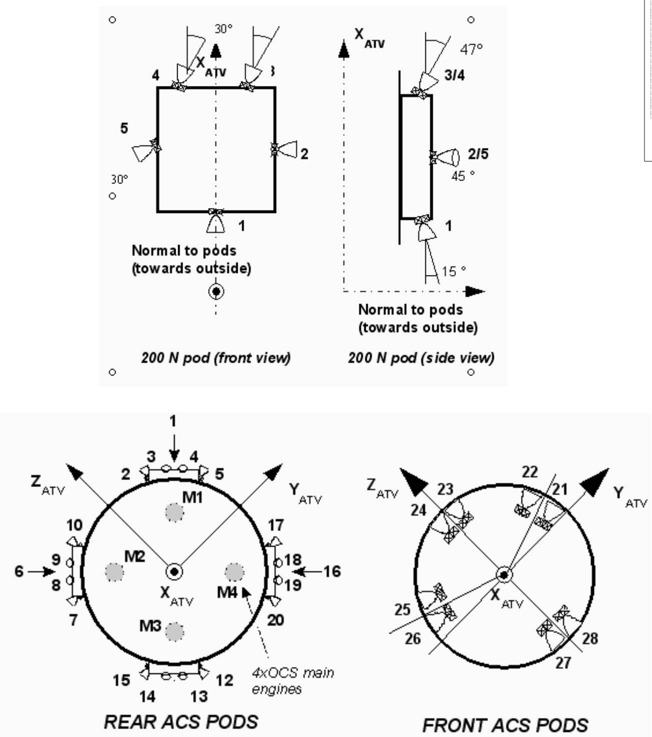

Figure 2 ATV Attitude Control System thrusters pods location

2.2 Architecture of the flight control loop

The architecture of the flight control loop of the ATV is summarised on the figure 3 after. The Thrust Management Function has to calculate at each 1 second cycle the proper jet selection and firing duration to realize the force and torque impulse command prescribed by the Control algorithm. The ACS thrusters Flow Control Valves (FCV) are commanded in a pulse mode. Each command is defined by its start date T_{ON} and its duration or the closing date T_{off}. These commands calculated by the TMF are distributed electrically to the thrusters Flow Control Valves (FCV) through a set of 4 Propulsion Drive Electronics (PDE). Each thruster is commanded by one PDE. The connection of the thrusters to the PDE is such that the translational and rotational control of the vehicle in RV is tolerant to the failure of one PDE (and/or any of the attached FCV). In the nominal configuration without failure, 20 jets are allocated to the GNC, the others being reserved for failure configurations and emergency braking manoeuvre. The single failure (PDE or thruster) configurations involve 15 jets at least. A total of 10 configurations are defined.

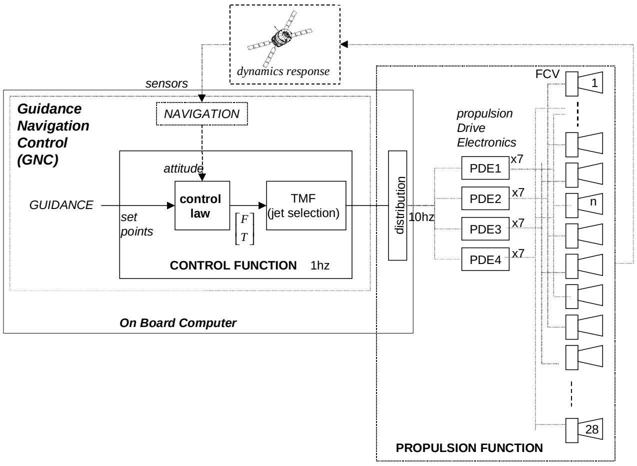

Figure 3 Vehicle control functional architecture

2.3 On Board Thruster Management Function (TMF)

The TMF shall finally realize the following tasks:

- the determination of the jet selection capable to realize the desired force and torque impulse with minimization as far as possible of the propellant consumption
- the calculation of each jet firing duration taking into account firing constraints
- the determination of the command dates of the FCV commands in the 1s cycle

We will focus namely on the two first aspects in this paper.

2.4 Jet firing Scheduling Constraints for the ATV Thruster Management Function

The thrusters commands Ton, Toff are subject to the scheduling constraints:

- (a) command duration between 0 and 1s in consistency with the Control cycle period
- (b) (thermal constraint) a maximum of 4 ACS thrusters can be activated ON for each PDE and each 1s cycle of command
- (c) For each ACS thruster, there is a minimum firing duration of 25msec (minimum Impulse Bit) and a minimum OFF duration for commands shorter than 1s.
- (d) Electrical limitation on the number of simultaneous ON commands on the same PDE, this constraint is managed by staggering the commands in excess with an interval of 100ms.

The constraints (a), (c), (d) are managed by the on board TMF algorithm. The constraint (b) is checked once at design stage on the precomputed thrusters set of the catalogue table.

3. OPTIMAL THRUSTER SELECTION LOGIC

The TMF shall determine at each cycle the jet selection and firing duration that realizes the resultant mean force F and mean torque T over the command cycle as required by the Control loop algorithm. This condition can be formulated under the linear form:

$$A\mathbf{x} = \mathbf{b}$$

$\mathbf{b}=(F1c,F2c,F3c,T1c,T2c,T3c)^t$ is the co-ordinate column matrix of the mean Force and Torque commanded expressed in the reference body fixed vehicle frame.

$\mathbf{x}=(x1,x2,...xN)^t$ is the command vector whose components $xi=\Delta ti$ ($1\leq$ i $\leq$ N) are the firing duration commanded for each jet

A=(A1,A2,..,AN) is the force/torque response matrix of the thrusters, its columns $Ai=(Fi1,Fi2,Fi3,Ti1,Ti2,Ti3)^t$ represent each thruster force and torque co-ordinates in the vehicle body frame.

Constraint general model : the vector x is subject to the general constraint (a) above , $0\leq \mathbf{x} \leq 1$, the constraint (c) on the minimum Ton/Toff is not taken into account at the jet selection step to avoid complications.

Optimisation criterion. The jet selection can be based on a propellant consumption criterion that has the form:

$$\min \mathbf{c.x} = \sum_{i=1}^{i=N} c_i . x_i$$

where $\mathbf{c}i>0$ is a factor proportional to the thruster (i) efficiency, $\mathbf{c}i=1$ is convenient if all the thrusters have the same efficiency.

3.1 General Statement of the Jet Selection Problem.

Summarising the conditions above, the optimal command $\mathbf{x}=(x_1,...,x_N)^t$ *is* solution of the linear programming problem

$$\{\min \mathbf{c.x} \ / \ \mathbf{0}\leq \mathbf{x} \leq \mathbf{1}, \mathbf{Ax} = \mathbf{b}\} \quad (1).$$

Such a class of problem is generally solved by means of the Simplex method [2].

3.2 Jet Selection Logic from a Catalogue as an Alternative to the Simplex Method.

The Simplex method is commonly considered as the most efficient in practice to solve the problem (1) stated as above and this method has been then a first candidate algorithm for the 6 d.o.f. TMF in the early stage of ATV development. However the preliminary studies on the Simplex algorithm showed that the processing power needed by this algorithm was too high for the on board processing budget. To reduce the processing power consumption the present method has been conceived and developed based on a precomputed set of optimal jet selection solutions (we denominate it the optimal catalogue method). In addition to the processing power reduction objective the following drivers were also in favour of the catalogue method:

- the statistical rather than deterministic bounds of iteration number in the simplex with a theoretical difficulty to define the absolute bounds on this number (at a feasible value), although reasonable at the average
- the problem of cycling that can occur in some cases in the simplex method that may happen when a flat cost variation occurs. Adaptations may complicate and slower the Simplex algorithm.
- the worst case accuracy of the commands can be evaluated in a deterministic way with the catalogue method rather than statistically with the Simplex method where the final inverse matrix is obtained by successive basis change, some of them possibly poorly-conditioned.
- the verification on the number of jet ON per PDE (constraint (b) before), can to be verified in a deterministic way in the catalogue.

4. PRINCIPLE OF THE OPTIMAL JET COMMAND BY CATALOGUE

The principle of the On Board optimal algorithm of jet selection and command by catalogue is illustrated on the figure 4.

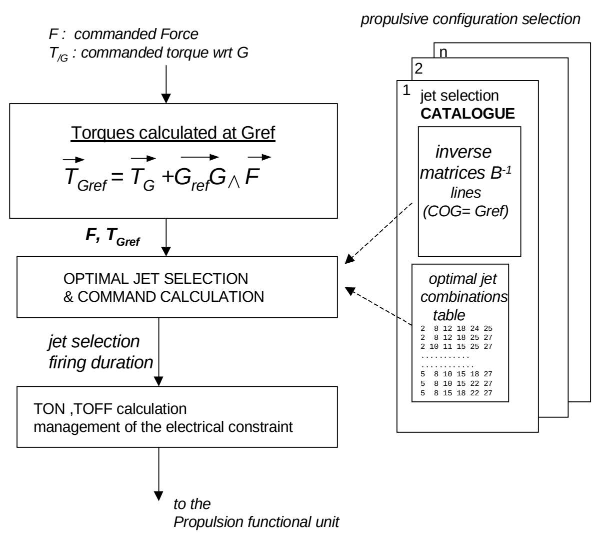

Figure 4 Functional synoptic of the optimal jet command by catalogue

The input are the mean Force and Torque vectors co-ordinates commanded by the Control function. The torque is expressed with respect to the current Center of Gravity (COG) of the vehicle. The current usable propulsion set configuration is also defined by the overall propulsion management function. The data of the catalogue corresponding to this configuration are pre-stored, one table contains all the possible jet set solutions that can be commanded, an other table contains the corresponding inverse matrix allowing the firing command calculation.

4.1 Expression of the Commanded Torque in the Catalogue Origin

The catalogue of solution is calculated using one fixed reference frame for the expression of the Force and Torques. The system of axis is chosen parallel to the conventional ATV body axis but the origin is fixed in a conventional way. The torque prescribed with respect to the current vehicle COG can be converted with respect to the conventional origin of the catalogue by the relation

$$\vec{T}_{Gref} = \vec{T}_G + \overrightarrow{G_{ref}G} \wedge \vec{F} \qquad (2)$$

This linear relation guarantees the validity and optimality of the catalogue with respect to COG variations. This is not possible in the case of 3 d.o.f. only rotation control because the force F intervening in the relation (2) is not controlled , then not predicted.

4.2 Simplified Statement of the Optimal Problem

The formulation of the optimal command under constraint has been expressed under a little more simple form, in order to obtain a set of solution of reasonable complexity:

$\mathbf{x}^*$ solution of $\{ Min(\mathbf{c}.\mathbf{x}) \,/\, \mathbf{x} \geq 0 \,,\, \mathbf{Ax}=\mathbf{b} \}$ (3)

$\mathbf{x} = \mathbf{x}^*/max\{1 \,,\, x^*_i \,,\ for\ i=1\ to\ N\}$ (4)

The latter expression is no more than the application of a linear saturation.

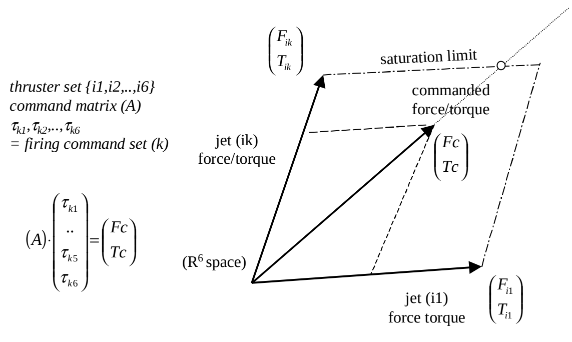

Figure 5 principle of linear saturation

The difference with the formulation (1) is that the upper constraint $x \leq 1$ is not handled in the optimisation problem but by the post-processing saturation that can be interpreted as the application of a same saturation factor to the force and torque realised as illustrated on figure 5. This provides solutions having the best efficiency in term of ratio (force, torque)/consumption in the direction of the force/torque commanded.

In the linear programming problem (3) the constraint (6xN) matrix [A] has the rank 6, which is also the dimension of the "basic" solutions of the problem. The optimal solutions can then to be found among the combinations of 6 jets and the dimension of the catalogue table is then fixed to 6 jets per selection. In degenerate cases at the optimum, some non basic variable may have a null reduced cost, the corresponding jet could be added to the 6 jet solution without propellant cost impact. This could improve the maximum force torque deliverable but the jet selection sets of the catalogue table has been limited to a fixed dimension for the algorithm simplification.

4.3 Design of the Catalogue Table

The on board TMF catalogue comprises one table defining all the combinations of 6 jets needed to realise optimally any force/torque direction commanded, one complementary table containing the inverse transfer matrices associated to each jet combination of the first table, and one index table.

The TMF catalogue tables are precomputed once a time in the design phase as a function of the force torque thrusters characteristics with respect to a fixed vehicle frame and origin. This determination takes into account the criterion of propellant consumption minimization. The method that has been developed internally determines all the six jet optimal combinations and ensures that the overall jet combination constituting the catalogue allows the whole force torque commandability of the vehicle in any direction.

4.4 On Board Jet Selection and Command Calculation

This is the second step (cf figure 4) of the TMF algorithm. For each optimal 6 thrusters set (k1,k2,...,k6) of the catalogue table stored on board, the commands $(x_{k1},x_{k2},..x_{k6})$ without saturation are calculated by:

$$(x_{k1},x_{k2},..x_{k6})^t = \mathbf{A}_k^{-1} \begin{pmatrix} F \\ T_{Gref} \end{pmatrix} \qquad (5)$$

$\mathbf{A}_k^{-1}$ is the inverse transfer matrix of the thrusters k1,k2,...k6 stored in the on board inverse matrix tables.

$\boldsymbol{F}$ commanded force ; $\boldsymbol{T_{Gref}}$ commanded torque/Gref

We define one opening command *x* as feasible if $x \geq 0$. An important property of the catalogue of solution is that if a command is feasible, it is also optimal. The selection of the jet set solution has then been based on the feasibility condition. To check this condition it is necessary to calculate the commands by the relation (5) for all the jet set of the selected propulsive configuration. To avoid rejecting the good solution because of numerical accuracy ($x = +- \varepsilon$), the selected set of 6 jets is the one that gives the maximum of *min{xk1,xk2,..xk6}*.

The potentially residual slightly negative commands are rounded to zero in the final step of the algorithm.

Some other improved methods were also envisioned at the early stage of the design (among them one based on a dual criterion maximisation); the method based here on the feasibility criterion was chosen for its simplicity, robustness and as its processing power need was compliant with the improvement objectives.

4.5 Rounding the Ton Toff Duration

In the final step of the algorithm, the commands are rounded for the constraints of minimum firing duration and minimum OFF duration between pulses on the same thrusters.

5. SIZING OF THE TMF BY CATALOGUE FOR THE ATV

Despite there is a huge number of combination of 6 thrusters among 20 (maximum) available for the nominal configuration, one important result is that the number of optimal set solutions is quite reasonable. The number of 6 thrusters solutions set is Nset=283 with the nominal configuration and Nset=140 for the failure propulsive configurations of 15 thrusters. Without storage optimisation, the memory size of the nominal case table is 47.5Kbytes (counting all data on 32bits even the integers). Taking into account 10 propulsive configurations the total number of 6 jet set amounts to 1855. They were no attempt to compress the data by exploiting the jet set data redundancy in the overall table, to avoid a degradation of the processing performance, but however the matrix lines colinearity are exploited internally to each propulsive configuration catalogue for a gain of 25% on the tables size (including an additional pointers table needed).

The processing power needed by the catalogue algorithm is corresponding to 36*Nset floating operations, then 30ms for the ATV computer to be compared with the former need estimated to 128ms with the Simplex.

Code Complexity

The TMF on board algorithm is extremely simple as it represents about 80 executable instructions in its FORTRAN version.

Maximum Level of Force Evaluation

The level of the maximum resultant force that the TMF can deliver is an important factor in the sizing of the RV trajectories like those of Homing and Closing (cf [1]). As the catalogue method limits to 6 the number of jet fired at each cycle, then the level of maximum deliverable force is lower than the theoretical maximum force deliverable. On the counterpart the specific consumption[†] is optimal. Some comparisons of the theoretical maximum force level commandable using the Simplex algorithm programmed with the complete model of equation (1) have been performed showing that the maximum force with the 6 jet combinations of the catalogue was 30% below the theoretical maximum (without the 6 jet limitation).

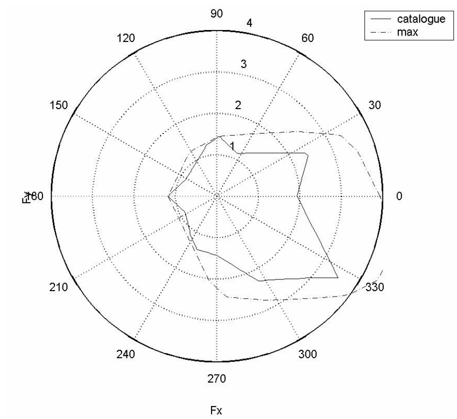

Figure 6: force capability compared with maximum force (case PDE2 failed)

Accuracy

The catalogue of preselected jet gives the possibility to check the matrix condition number C(A) of the transfer matrices A, the inverse matrix accuracy is related to this factor. The condition number of a matrix A may be defined by the relation[*] C(A)= (||A||.||A-1||). The indefinite norm defined by

||A||=max i {|ai1|+|ai2|+...+|aiN|}

is suitable for this evaluation. The figure 7 hereafter shows that the inverse condition number 1/C(A) of the catalogue jet selection matrices in the nominal propulsive configuration is greater than 0.001 , corresponding to about 3 digit loss of accuracy, which is satisfactory.

[†] specific consumption is defined here as the ratio (consumption per cycle / resutant mean force)

[*] the definition may depending on the authors, often it is defined as $C=1/\|A\|.\|A^{-1}\|$

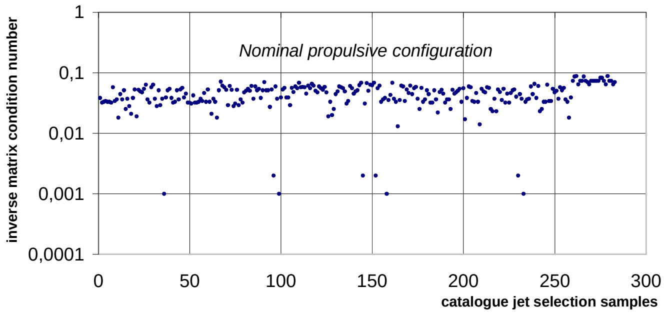

Figure 7 Inverse matrix condition number for each 6 jet selection

Optimality

The figure 8 shows with the same type of random commands input in the range of force/torque without saturation, the agreement between the consumption of the commanded jet selection of the TMF by catalogue and the optimal consumption from the TMF programmed with the Simplex.

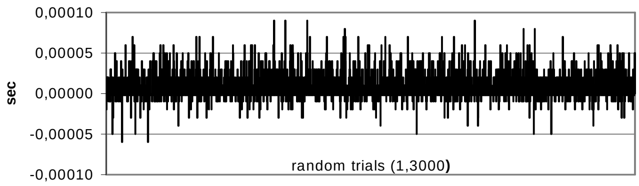

Figure 8 difference on the consumption index (s) between Catalogue/Simplex

6. TESTS ON SIMULATION BENCH

The TMF has been tested in a closed loop simulation of the ATV Guidance Control study simulation bench in RV providing comparable results with the same simulation executed with a TMF based on the Simplex iterative algorithm. The 6 d.o.f TMF undergoes the flight control simulation studies successfully since almost 3 years.

7. CONCLUSION

The TMF principle presented relies on a new catalogue table design with promising application. It proves to be compatible with the processing power and memory size of today on board computer. It affords significant advantages as it is compatible with non axis-symmetric propulsion architecture even with complex coupling effects, it permits to verify since the vehicle design stage the compatibility of each combination of jets of the catalogue with the thermal and electrical constraints of the command equipments. The numerical quality of the catalogue matrices can also be pre-checked and the number of calculation is deterministic (no convergence statement). In addition the command is optimal on consumption in transparency with the center of mass variations. On the other side, due to the principle of the limited number of simultaneous firing jets commanded, the maximal mean force / torque level realized is not generally the absolute maximum feasible by the propulsion architecture but the method is well suited for propulsion architectures composed of thrusters with homogeneous unitary thrust level.

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