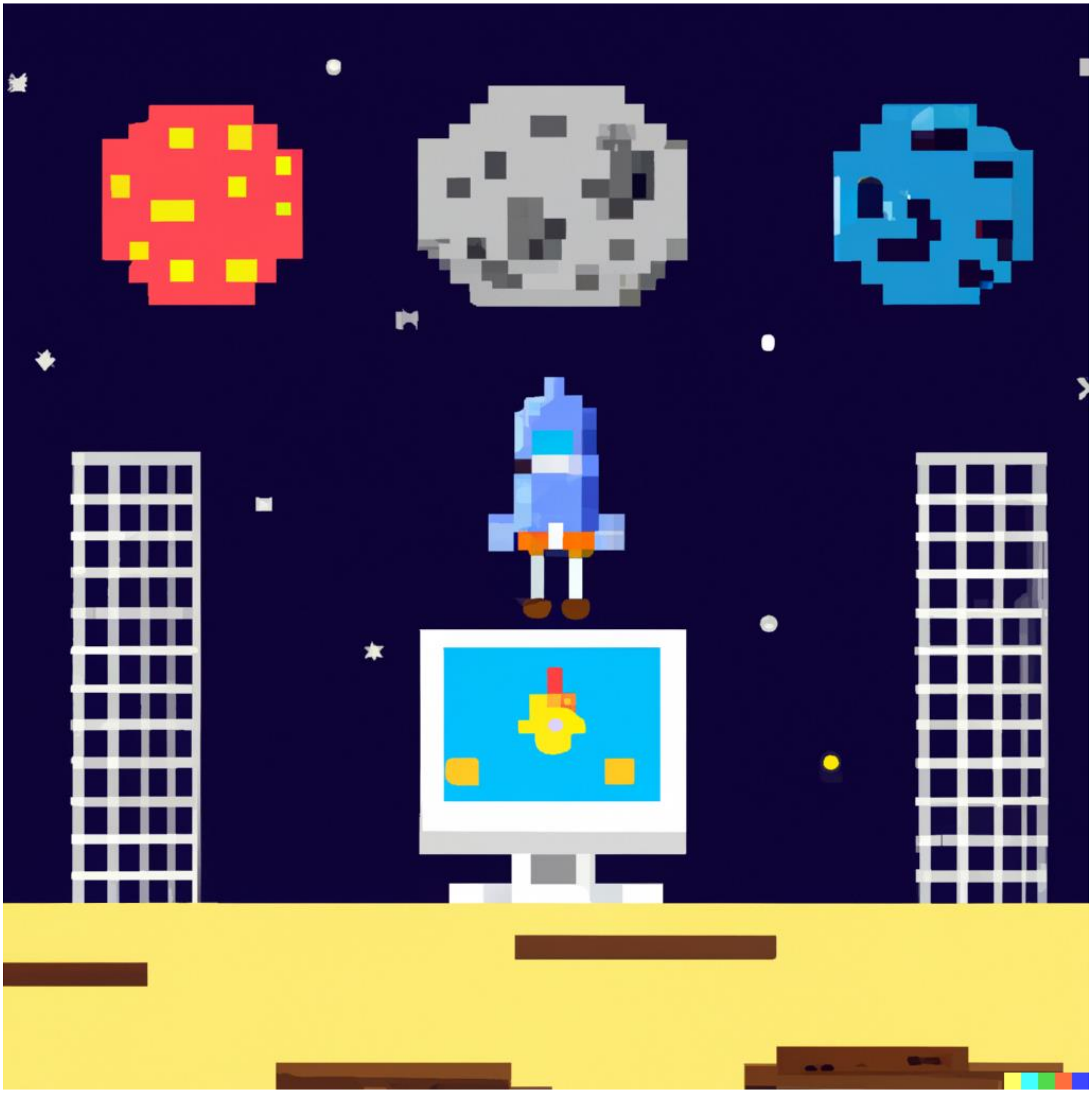


Thruster FDIR

By Chandrabhraman

1.1 Introduction:

The method used here falls under the category of model based fault diagnosis. It uses a model, and one or more measurements that are sampled regularly.

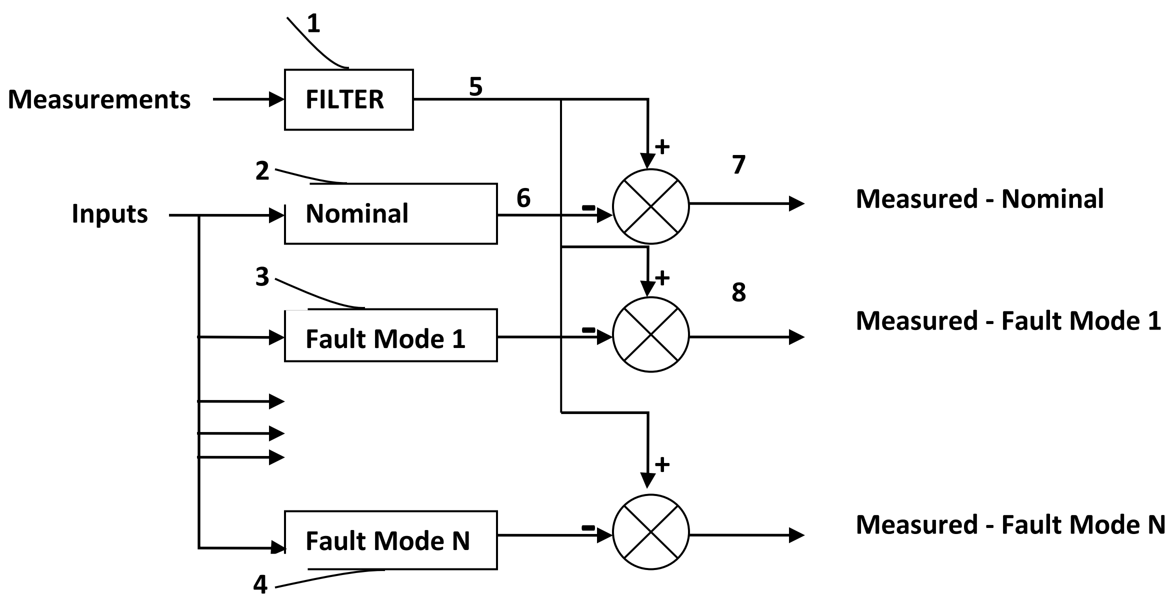
These algorithms can be implemented on-board using the spacecraft's existing processor(s), on-board using a stand-alone processor, or on the ground, processing sensor information communicated to the ground stations from the spacecraft.

A mean square based approach to thruster FDI for spacecraft was developed. The system uses gyro signals (and accelerometers if desired) to detect and isolate hard, abrupt single- and multiple-jet on- and off-failures. *But, presently the fault model presented here deals with one thruster failure at a time only.* Similar method was applied on X-38[1] in which faults are detected within one second and identified within one to five seconds in most of the cases.

1.2 Description of the method:

1.2.1 Disturbing & Residual accelerations:

If a thruster has failed then this would have an effect on the said actual measurements. Corresponding to that thruster, if failed there is a fixed value of acceleration. These pre-determined acceleration values along with the measurement values are used to detect when a fault is present. So, this method is based on the similarity of measured acceleration with the accelerations corresponding to the faulty modes. As described in the fig. given below:



- **1** Measurement update/ Filter
- **5** Estimated actual system output
- **2 to 4** Possible thruster failure modes
- **6** Predicted system output using dynamics

- **7** $\hat{\mathbf{a}}_{\text{disturbing}}$ is ***Disturbing acceleration***. It is deviation of measured value of acceleration vectors ($\hat{\alpha}$ and $\hat{\ddot{X}}^{\text{body}}$) from the nominal values $\boldsymbol{\alpha}_{\text{nominal}}$ and $\ddot{X}^{\text{body}}_{\text{nominal}}$ in body frame.
  - Linear & Angular acceleration both are combined to give 6x1 vector .
  - $\hat{\mathbf{a}}_{\text{disturbing}} \triangleq \hat{a} - a_{\text{nominal}} = \begin{bmatrix} \hat{\alpha}_{\text{disturbing}} \\ \hat{\ddot{X}}_{\text{disturbing}} \end{bmatrix} \triangleq \begin{bmatrix} \hat{\alpha} & - & \alpha_{\text{nominal}} \\ \hat{\ddot{X}}^{\text{body}} & - & \ddot{X}^{\text{body}}_{\text{nominal}} \end{bmatrix}$
- **8** $\mathbf{a}_{\text{residual, 1}}$ is ***Residual acceleration*** for ***fault mode 1.*** It is the residual between measured value of acceleration & the nominal accelerations corresponding to fault mode1.
  - $\mathbf{a}_{\text{deviation, i}} \triangleq \mathbf{a}_{\text{fault\_mode i}} - a_{\text{measured}} = \begin{bmatrix} \alpha_{\text{deviation}} \\ a_{\text{deviation}} \end{bmatrix} \triangleq \begin{bmatrix} \alpha_{fault\ mode\ i} - \alpha_{\text{estimated}} \\ a_{fault\ mode\ i} - \ddot{X}^{\text{body}}_{\text{measured}} \end{bmatrix}$

The fault mode acceleration $\mathbf{a}_{\text{fault\_mode i}}$ values may be pre-calculated and can be directly viewed from the table based on inputs only.

1.2.2 Fault Modes

Lets say a block of 4 thrusters are chosen as per requirement of attitude control in yaw, pitch, roll axes. This is done through a TSL (Thruster Selection Logic) which maps the requirements of attitude control to combination of thrusters chosen. Fault modes are decided for each of the thruster blocks independently.

Consider the thruster block {1, 2, 3, 4}.
There will be 4 failure modes depending upon which thruster has failed. So,
Failure mode 1: T1 failed
Failure mode 2: T2 failed
Failure mode 3: T3 failed
Failure mode 4: T4 failed

Failure mode 1, i.e., T1 failed has further 7 sub cases. From the TSL table it seems that Thruster 1 is used in 10 cases, so it should be 10 sub cases. However, due to the presence of 3 redundant cases of
T1 = 1, T2 = 0, T3 = 0, T4 = 0
Number of sub cases reduces to 7 only for each fault mode.

The case of (7*4 =) 28 failure cases (or failure sub modes) can also be concluded using the following intuition. TSL table as shown below of the considered thruster block consists of 27 rows, each consisting of 1's showing the thrusters used to attain the required attitude. Considering row 1, (1, 1, 1, 0) firing, 3 sub cases either T1 failed, or T3 or T4. And removing redundant cases (as marked orange for T2), 28 cases in total.

Yaw	Pitch	Roll	T1	T2	T3	T4	Total fault cases
1	1	1	1	1	1	0	3

Yaw	Pitch	Roll	T1	T2	T3	T4	
1	1	1	1	1	1	0	3

1	1	0	0	1	0	0	1
1	1	-1	0	1	0	0	1
1	0	1	1	0	0	0	1
1	0	0	1	1	0	0	2
1	0	-1	0	1	0	0	1
1	-1	1	1	0	0	0	1
1	-1	0	1	0	0	0	1
1	-1	-1	1	1	0	1	3
0	1	1	0	0	1	0	1
0	1	0	0	1	1	0	2
0	1	-1	0	1	0	0	1
0	0	1	1	0	1	0	2
0	0	0	0	0	0	0	0
0	0	-1	0	1	0	1	2
0	-1	1	1	0	0	0	1
0	-1	0	1	0	0	1	2
0	-1	-1	0	0	0	1	1
-1	1	1	0	0	1	0	1
-1	1	0	0	0	1	0	1
-1	1	-1	0	1	1	1	3
-1	0	1	0	0	1	0	1
-1	0	0	0	0	1	1	2
-1	0	-1	0	0	0	1	1
-1	-1	1	1	0	1	1	3
-1	-1	0	0	0	0	1	1
-1	-1	-1	0	0	0	1	1
0	0	0	10	10	10	10	40

Removing redundant cases from these 40 cases provides us only 28 cases.

Sub cases of Fault mode 1: (T1 failed)

Yaw	Pitch	Roll	T1	T2	T3	T4
1	1	1	X	1	1	0
1	1	0	0	1	0	0
1	1	-1	0	1	0	0
1	0	1	X	0	0	0
1	0	0	X	1	0	0
1	0	-1	0	1	0	0
1	-1	1	X	0	0	0
1	-1	0	X	0	0	0
1	-1	-1	X	1	0	1

Redundant cases

0	1	1	0	0	1	0
0	1	0	0	1	1	0
0	1	-1	0	1	0	0
0	0	1	X	0	1	0
0	0	0	0	0	0	0
0	0	-1	0	1	0	1
0	-1	1	X	0	0	0
0	-1	0	X	0	0	1
0	-1	-1	0	0	0	1
-1	1	1	0	0	1	0
-1	1	0	0	0	1	0
-1	1	-1	0	1	1	1
-1	0	1	0	0	1	0
-1	0	0	0	0	1	1
-1	0	-1	0	0	0	1
-1	-1	1	X	0	1	1
-1	-1	0	0	0	0	1
-1	-1	-1	0	0	0	1

$\}$ **Redundant cases**

Sub cases of Fault mode 2: (T2 failed)

Yaw	Pitch	Roll	T1	T2	T3	T4
1	1	1	1	X	1	0
1	1	0	0	X	0	0
1	1	-1	0	X	0	0
1	0	1	1	0	0	0
1	0	0	1	X	0	0
1	0	-1	0	X	0	0
1	-1	1	1	0	0	0
1	-1	0	1	0	0	0
1	-1	-1	1	X	0	1
0	1	1	0	0	1	0

0	1	0	0	X	1	0
0	1	-1	0	X	0	0
0	0	1	1	0	1	0
0	0	0	0	0	0	0
0	0	-1	0	X	0	1
0	-1	1	1	0	0	0
0	-1	0	1	0	0	1
0	-1	-1	0	0	0	1
-1	1	1	0	0	1	0
-1	1	0	0	0	1	0
-1	1	-1	0	X	1	1
-1	0	1	0	0	1	0
-1	0	0	0	0	1	1
-1	0	-1	0	0	0	1
-1	-1	1	1	0	1	1
-1	-1	0	0	0	0	1
-1	-1	-1	0	0	0	1

Sub cases of Fault mode 3: (Thruster 5 failed)

Yaw	Pitch	Roll	T1	T2	T3	T4
1	1	1	1	1	X	0
1	1	0	0	1	0	0
1	1	-1	0	1	0	0
1	0	1	1	0	0	0
1	0	0	1	1	0	0
1	0	-1	0	1	0	0
1	-1	1	1	0	0	0
1	-1	0	1	0	0	0
1	-1	-1	1	1	0	1
0	1	1	0	0	X	0
0	1	0	0	1	X	0

0	1	-1	0	1	0	0
0	0	1	1	0	X	0
0	0	0	0	0	0	0
0	0	-1	0	1	0	1
0	-1	1	1	0	0	0
0	-1	0	1	0	0	1
0	-1	-1	0	0	0	1
-1	1	1	0	0	X	0
-1	1	0	0	0	X	0
-1	1	-1	0	1	X	1
-1	0	1	0	0	X	0
-1	0	0	0	0	X	1
-1	0	-1	0	0	0	1
-1	-1	1	1	0	X	1
-1	-1	0	0	0	0	1
-1	-1	-1	0	0	0	1

Sub cases of Fault mode 4: (Thruster 8 failed)

Yaw	Pitch	Roll	T1	T2	T3	T4
1	1	1	1	1	1	0
1	1	0	0	1	0	0
1	1	-1	0	1	0	0
1	0	1	1	0	0	0
1	0	0	1	1	0	0
1	0	-1	0	1	0	0
1	-1	1	1	0	0	0
1	-1	0	1	0	0	0
1	-1	-1	1	1	0	X
0	1	1	0	0	1	0

0	1	0	0	1	1	0
0	1	-1	0	1	0	0
0	0	1	1	0	1	0
0	0	0	0	0	0	0
0	0	-1	0	1	0	X
0	-1	1	1	0	0	0
0	-1	0	1	0	0	X
0	-1	-1	0	0	0	X
-1	1	1	0	0	1	0
-1	1	0	0	0	1	0
-1	1	-1	0	1	1	X
-1	0	1	0	0	1	0
-1	0	0	0	0	1	X
-1	0	-1	0	0	0	X
-1	-1	1	1	0	1	X
-1	-1	0	0	0	0	X
-1	-1	-1	0	0	0	X

Renaming disturbing accelerations & residual acceleration according to sub cases of fault modes.
For the j^{th} case in fault mode i we define the following 6x1 vector:

$$\boldsymbol{a}_{\text{fault mode, } i,\, j} \triangleq \begin{bmatrix} \alpha_{fault\ mode\ i\ ,j} \\ a_{fault\ mode\ i,j} \end{bmatrix}$$

$$\hat{\boldsymbol{a}}_{\text{measured}} \triangleq \begin{bmatrix} \hat{\alpha} \\ \hat{\ddot{X}}^{body} \end{bmatrix}$$

$$\boldsymbol{a}_{\text{nominal}} \triangleq \begin{bmatrix} \alpha_{nominal} \\ \ddot{X}^{body}_{nominal} \end{bmatrix}$$

$$\boldsymbol{a}_{\text{residual, } i,\, j} \triangleq (\boldsymbol{a}_{\text{fault mode } i,\, j} - \boldsymbol{a}_{\text{measured}})$$

$$= \begin{bmatrix} \alpha_{residual,\ i,\ j} \\ a_{residual,\ i,\ j} \end{bmatrix} \triangleq \begin{bmatrix} \alpha_{fault\ mode\ i,j} - \hat{\alpha} \\ a_{fault\ mode\ i,j} - \hat{\ddot{X}}^{body} \end{bmatrix}$$

While disturbing acceleration remains same as,

$$\hat{a}_{disturbing} \triangleq (\hat{a} - a_{nominal}) = \begin{bmatrix} \hat{\alpha}_{disturbing} \\ \hat{\ddot{X}}_{disturbing} \end{bmatrix} \triangleq \begin{bmatrix} \hat{\alpha} - \alpha_{nominal} \\ \hat{\ddot{X}}^{body} - \ddot{X}^{body}_{nominal} \end{bmatrix}$$

These are the estimated values of α and a from Gyro and accelerometer data. Now, if there are no faults in any of the thrusters then $\begin{matrix} \hat{\alpha} \\ \hat{\ddot{X}}^{body} \end{matrix}$ estimated values will be close to nominal values $\begin{matrix} \alpha_{nominal} \\ \ddot{X}^{body}_{nominal} \end{matrix}$ *(not time shifted values, It needs thruster performance during the control period)*

1.2.3 Calculation of $\alpha_{nominal}$, $\ddot{X}^{body}_{nominal}$ and estimation of $\hat{\alpha}$ & $\hat{\ddot{X}}^{body}$ from measurement data

At control update k,

$$\alpha_{nominal,k} = I^{-1}\left((L\mathrm{x}D)F_{nom}T_{command,k} + \tau_{disturb} - \omega\,\mathrm{x}(I\omega)\right)$$

$$\ddot{X}^{body}_{nominal,k} = m^{-1}DF_{nom}T_{command,k} + F^{body}_{disturb}$$

- $\boldsymbol{\omega}$ **-** A 3-by-1 vector containing the angular velocity of the body-fixed frame with respect to an inertial reference frame;
- $\boldsymbol{I}$ - A 3-by-3 matrix containing the spacecraft inertia tensor (also, dyadic, matrix), measured
- about the true center of mass;
- $\boldsymbol{L}$ **-** 3-by-n matrix containing x-y-z location of each thruster in the body frame;
- $\boldsymbol{D}$ - 3-by-n matrix containing unit vectors indicating the direction of thrust in the body frame;
- $\boldsymbol{F_{nom}}$- n-by-n diagonal matrix containing nominal strength of each thruster at full tank pressure;
- $\boldsymbol{T_{command,k}}$ - n-by-l vector of l's and 0's containing effective value for Which thrusters are at time step k, accounting for transient effects;

- $\boldsymbol{\tau_{disturb}}$ - 3-by-l vector containing sum of all torques on the vehicle resulting from other sources (drag, gravity gradient, separately modeled known thruster anomalies, CMG, RWA, and other calculable dynamic effects, etc.);
- $\boldsymbol{m}$ - scalar containing total vehicle mass;
- $\boldsymbol{F_{disturb}^{body}}$ - 3-by-l vector containing the net force on the vehicle through the center of mass, and the body superscript indicates measurement in the body frame

$\widehat{\ddot{X}}^{body}$ is directly measured from accelerometer data
While $\hat{\alpha}$ is **estimated** from Angular velocities as obtained from Gyroscope data.

1.2.4 Active and Inactive

We classify Fault modes as Active and Inactive to Improve accuracy by explicitly checking the data at times when the fault mode if present, should be causing deviation from nominal as well as checking at times when it should not be causing any deviation from nominal, even if it is present.

Active: A fault mode is said to be active if it would affect the system behavior if the mode were true.
E.g; if fault mode 1 is thruster number 1 failed off, and thruster 1 is commanded to fire, then fault mode 1 is active.

Inactive: A fault mode is said to be inactive if it would not affect the system behavior even if the mode were true.
E.g: in previous example if thruster no. 1 is not commanded to fire then fault mode 1 would be inactive

1.2.5 Data windowing

Since **Residual acceleration** provides us the measure of deviation of measurement data from the fault sub case acceleration data, matching of measurement signature with the signature of a particular fault sub case makes its corresponding fault mode likely to be true.

For e.g., if firing is as {1, 0, 1, 1} at time t,
Then **at that time** possible fault sub cases

- {X, 0, 1, 1} Corresponds to T1 failed (Fault mode 1) , Matching of measurement with this makes T1 to be failed
- T2 failed (Fault mode 1) is inactive at this time.
- {1, 0, X, 1} Corresponds to T3 failed (Fault mode 3) , Matching of measurement with this makes T2 to be failed
- {1, 0, 1, X} Corresponds to T4 failed (Fault mode 4) , Matching of measurement with this makes T4 to be failed

The method used here to measure the closeness of the match between them is least square method.

Due to the measurement noise and system disturbances unrelated to the faults, the decision to exonerate the fault modes are carried out through **Statistical based filtering on windows of historical**

data RATHER than on data at single point of time. As shown in fig., the windows is populated continuously either by $a_{residual,\, i,\, j}$ or by $\hat{a}_{disturbing}$ values.

Consider Fault mode T1, Active/Inactive (0 = Inactive, 1 = Active) represents whether at time t the controller fires thruster T1 or not. So,

If T1 is commanded to fire

- Store '**1**' in 2nd row of Fault mode T1 (Active)
- Store '$a_{residual,\, 1,\, j}$' where j is determined according to which other thrusters are commanded to fire at this time t. For example, if T1, T2, T4 are commanded to fire then j = 4 as picked up from the table which corresponds to YPR of 1, -1, 1.

If T1 is not commanded to fire

- Store '**0**' in 2nd row of Fault mode T1 (Inactive)
- Store '$\hat{a}_{disturbing}$'

Similarly, populate the rows corresponding to T2, T3 and T4 in the window.

Variable sized windows can also be used to collect data in different bins for different fault modes.

		T	T+16ms	T+32ms	T+48ms	T+64ms	T+80ms	
Fault mode T1	Acceleration values	$a_{residual,1,j}$	$a_{residual,1,j}$	$a_{residual,1,j}$	$\hat{a}_{disturbing}$	$a_{residual,1,j}$	$\hat{a}_{disturbing}$	MSE active
	Active/Inactive	1	1	1	0	1	0	MSE Inactive
Fault mode T2	Acceleration values	$a_{residual,2,j}$	$a_{residual,2,j}$	$\hat{a}_{disturbing}$	$\hat{a}_{disturbing}$	$\hat{a}_{disturbing}$	$\hat{a}_{disturbing}$	MSE active
	Active/Inactive	1	1	0	0	0	0	MSE Inactive
Fault mode T3	Acceleration values	$a_{residual,3,j}$	$\hat{a}_{disturbing}$	$\hat{a}_{disturbing}$	$\hat{a}_{disturbing}$	$a_{residual,3,j}$	$\hat{a}_{disturbing}$	MSE active
	Active/Inactive	0	0	0	0	1	0	MSE Inactive
Fault mode T4	Acceleration values	$a_{residual,4,j}$	$\hat{a}_{disturbing}$	$\hat{a}_{disturbing}$	$\hat{a}_{disturbing}$	$a_{residual,4,j}$	$a_{residual,4,j}$	MSE active
	Active/Inactive	1	0	0	0	1	1	MSE Inactive

At each time update, if the window is populated Mean square Error is calculated separately for active and inactive. Mean square error is chosen based upon the closeness of match between the corresponding fault modes and the measured deviation at both active and inactive times.

For fault mode i,

MSE $_{i,\ active}$ $\triangleq \begin{bmatrix} MSE_{i,active,angular\ acc} \\ MSE_{i,active,linear\ acc} \end{bmatrix}$

MSE $_{i,\ inactive}$ $\triangleq \begin{bmatrix} MSE_{i,inactive,angular\ acc} \\ MSE_{i,inactive,linear\ acc} \end{bmatrix}$

Mean Square Error :

$$\boldsymbol{MSE_{i,active,angular\ acc}} = \sum_k (\alpha_{fault\ mode\ i\ ,j} - \widehat{\alpha}\,)^T (\alpha_{fault\ mode\ i\ ,j} - \widehat{\alpha}\,)$$

Calculations of $(\alpha_{fault\ mode\ i\ ,j} - \widehat{\alpha}\,)$ are taken from the ***upper half*** of $\boldsymbol{a_{residual,i,j}}$ in the window consisting of only 1's.

While for

$$\boldsymbol{MSE_{i,active,linear\ acc}} = \sum_k (\, a_{fault\ mode\ i\ ,j} - \hat{\ddot{X}}^{body})^T (\, a_{fault\ mode\ i\ ,j} - \hat{\ddot{X}}^{body})$$

Calculations of $(\, a_{fault\ mode\ i\ ,j} - \hat{\ddot{X}}^{body})$ are taken from the ***lower half*** of $\boldsymbol{a_{residual,i,j}}$ in the window consisting of only 1's.

$$\boldsymbol{MSE_{i,inactive,angular\ acc}} = \sum_k (\widehat{\alpha} - \alpha_{nominal})^T (\widehat{\alpha} - \alpha_{nominal})$$

Calculations of $(\widehat{\alpha} - \alpha_{nominal})$ are taken from the ***upper half*** of $\boldsymbol{\widehat{a}_{disturbing}}$ in the window consisting of only 0's.

$$\boldsymbol{MSE_{i,inactive,linear\ acc}} = \sum_k \left(\hat{\ddot{X}}^{body} - \ddot{X}^{body}_{nominal} \right)^T (\hat{\ddot{X}}^{body} - \ddot{X}^{body}_{nominal})$$

Calculations of $\left(\hat{\ddot{X}}^{body} - \ddot{X}^{body}_{nominal} \right)$ are taken from the ***lower half*** of $\boldsymbol{\widehat{a}_{disturbing}}$ in the window consisting of only 0's.

Inference from MSE :

These expressions are calculated and used both to detect and to isolate failures.

When a fault mode i is true,

- $MSE_{i,active,angular\ acc}$ as well as $MSE_{i,active,linear\ acc}$ both will be **low**.

Since, the value $MSE_{i,inactive}$ is calculated using data from periods fault mode i was inactive. So, when there is no fault $MSE_{i,inactive}$ (both components) will have a **low** value. But whenever either

- Some other fault mode is true & is active, **or**
- Measurement error causing difference in Nominal acceleration values & Measured values.

$MSE_{i,inactive}$ Will have **high** values.

Then,

- So, high $MSE_{i,inactive}$ leads to exoneration of fault mode i.
- Confirmation of some other fault mode **j** as true fault mode if $MSE_{i,active,angular\ acc}$ & $MSE_{i,active,linear\ acc}$ both are low

1.2.6 Fault Detection Logic:

Loop over each fault mode

For fault mode i, when active readings are available in the window:

If $MSE_{i,active,linear\ acc}$ **< Threshold_act_linear_1** &
$MSE_{i,active,linear\ acc}$ **< Threshold_act_angular_1**
Then
T (i).count_continous = T (i).count_continous + 1;

// Fault Exoneration

Else
EXIT

1.2.7 Fault Exoneration Logic:

Loop over each fault mode

For fault mode i, when active readings are available in the window:

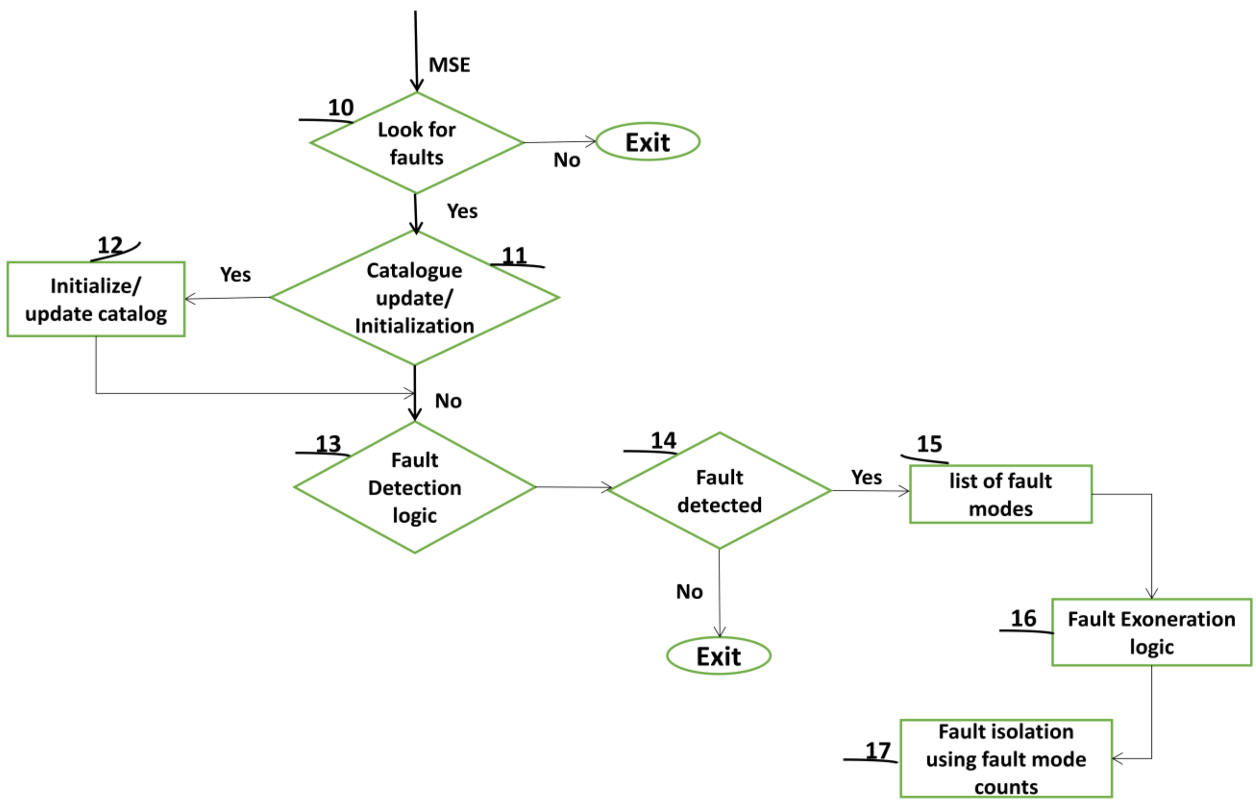
If $MSE_{i,inactive,linear\ acc}$ **> Threshold_inact_linear_1** &
$MSE_{i,inactive,linear\ acc}$ **> Threshold_inact_angular_1**
Then
T (i).count_continous = 0;

When fault mode i is true $MSE_{i,inactive}$ will have a low value, just as $MSE_{i,active}$ does. However when fault mode i is not true, it will have a high value whenever some other true fault mode j is active, and a low value at other times. $MSE_{i,inactive}$ is monitored for spikes and when the value exceeds a threshold, fault mode i is exonerated. Hence, when sensor data is faulty or too much noisy , no fault will be detected.

1.2.8 Fault Isolation:

If T(i).count_continous > 0
Then Fault mode i is true.

1.3 Flow chart



Each time, when updated set of MSE is generated following program logic is executed. This occurs at every minor cycle.

The following takes place during the thruster control period.

- **10** - Whether FDI is enabled so, when sensors are excessively noise, system disturbances are high then disable this.
- **11** - Checks to see if fault mode catalog requires initialization or update. If yes then $a_{fault\_mode,i,j}$ for the fault modes is updated using pre-calculated values in **12** for every possible fault mode i.

- **13** - Checks for fault detection using the thresholds. If yes, exoneration followed by isolation will be pursued. Otherwise if fault is still not detected in **13,** decision block **14** will exit the FDI processing until an updated set of MSE is received.

- If a fault is detected in **13,** the initial list of candidate faults is populated in **15** with all potential fault modes, and followed by immediate exoneration of as many possible in **16**

- After a fault is detected in **14** and clear match is determined in **17**, the fault mode is isolated.

1.3.1 Window size

Optimal selection of window size depends upon noise reduction needed, acceptable time before fault detection, and relative cost of false positive and failed detection. (Risk optimization). Also a minimum no. of samples of active data is needed before the mean square FDI analysis is allowed to proceed for a given fault mode.

1.3.2 Latency

A constant time has been assumed here for the latency. Which includes, the delay in the IMU data and the delay in thrust build up after a controller signal is generated.
So, if controller signal is generated at time $t = t_k$, then it's corresponding reaction on spacecraft will be measured by IMU,
Acceleration at $t = t_k + t\_latency\_accel + t\_thrust\_buildup$.
Similarly for **angular velocity** at $t = t_k + t\_latency\_gyro + t\_thrust\_buildup$

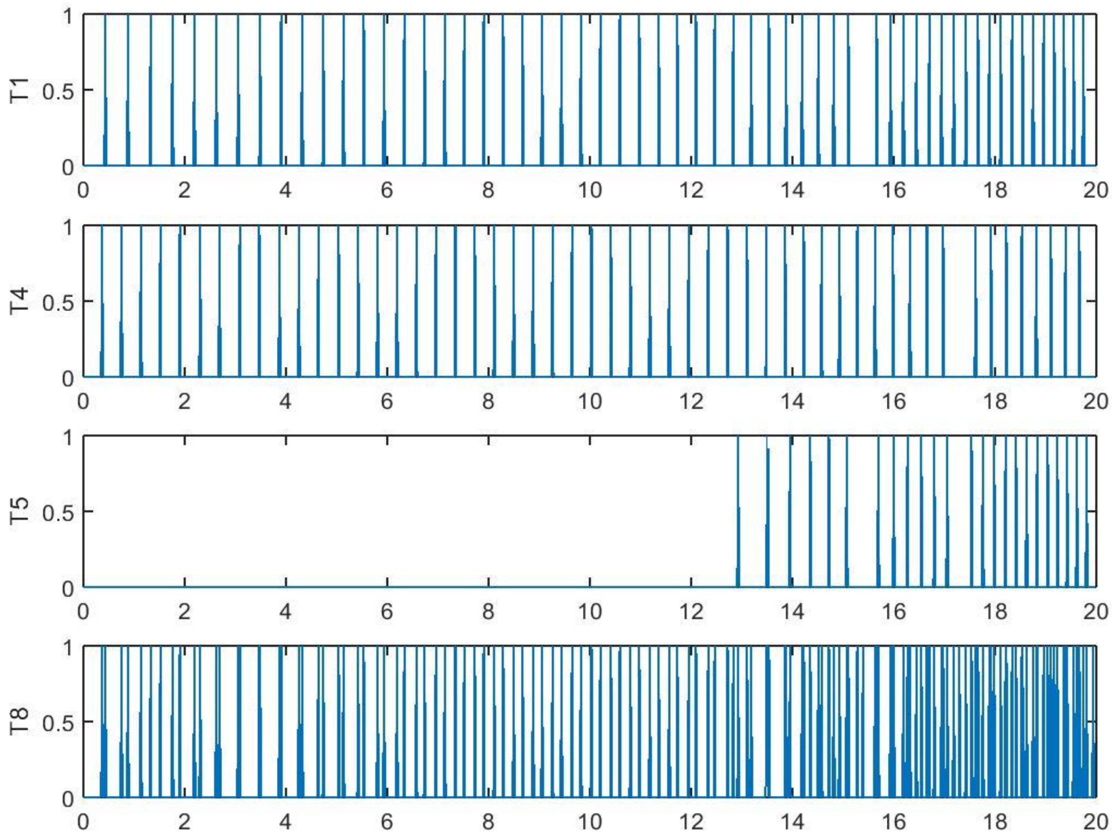
Working in discreet time domain, with the incremental time interval of **tinc**,
To synchronize the measured values with the controller generated commands, Acceleration values has to shifted backward **by *(t_latency_accel + t_thrust_buildup)/tinc*** steps while Gyro data has to shifted backward by
(***t_latency_accel + t_thrust_buildup)/tinc*** steps.

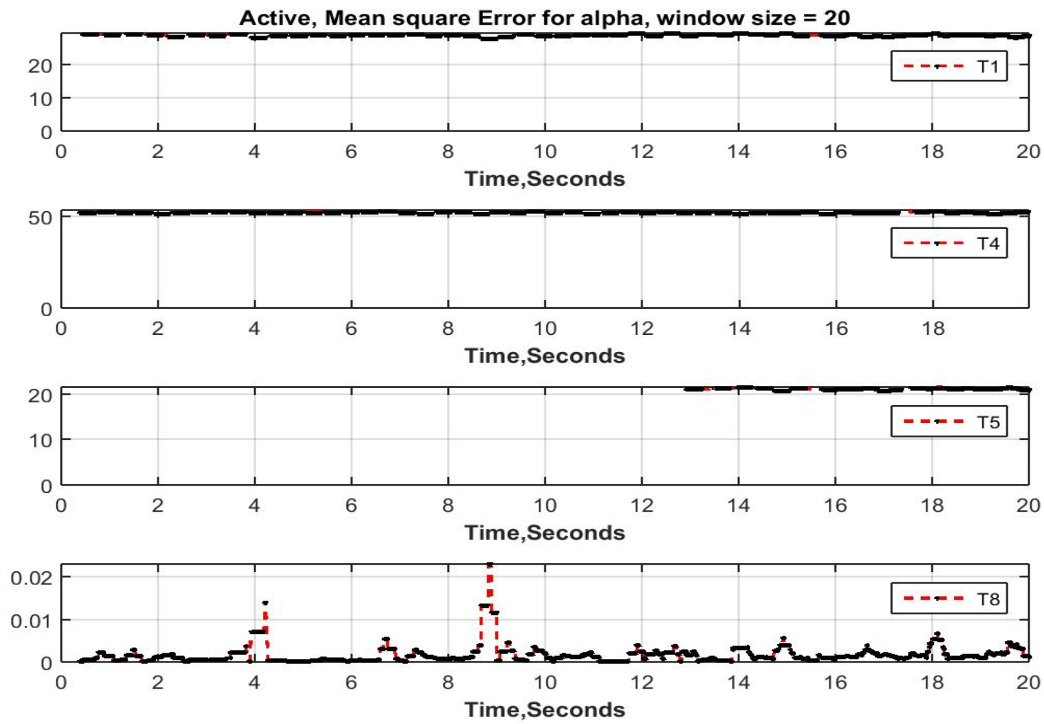
Further work can be done as in [6]

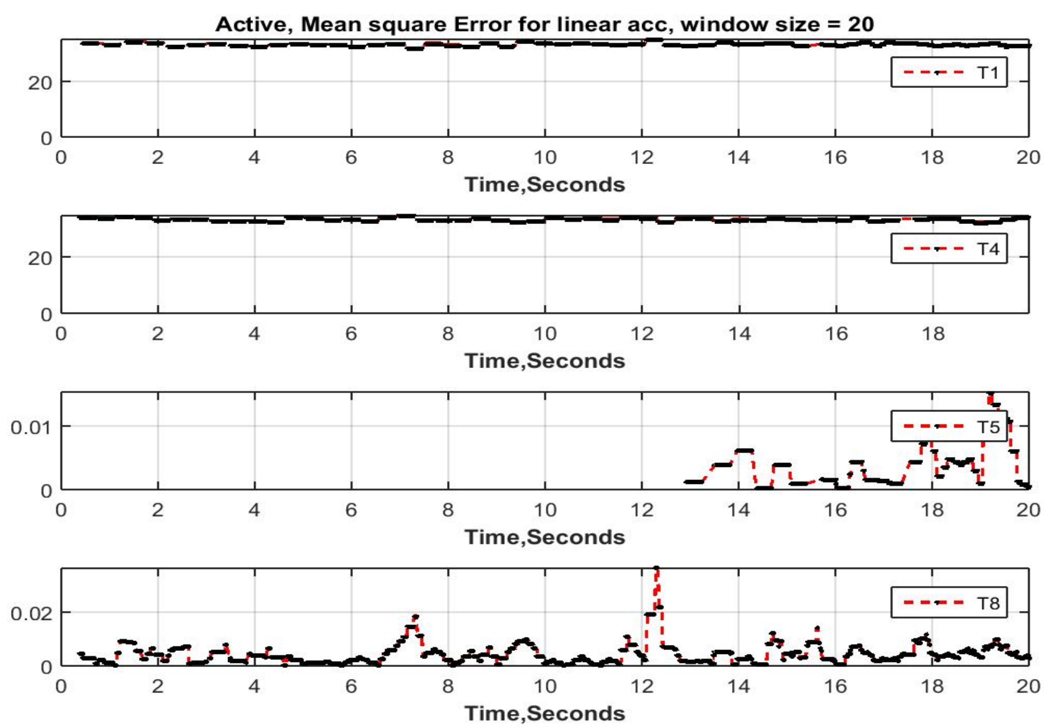
1.3.3 Results

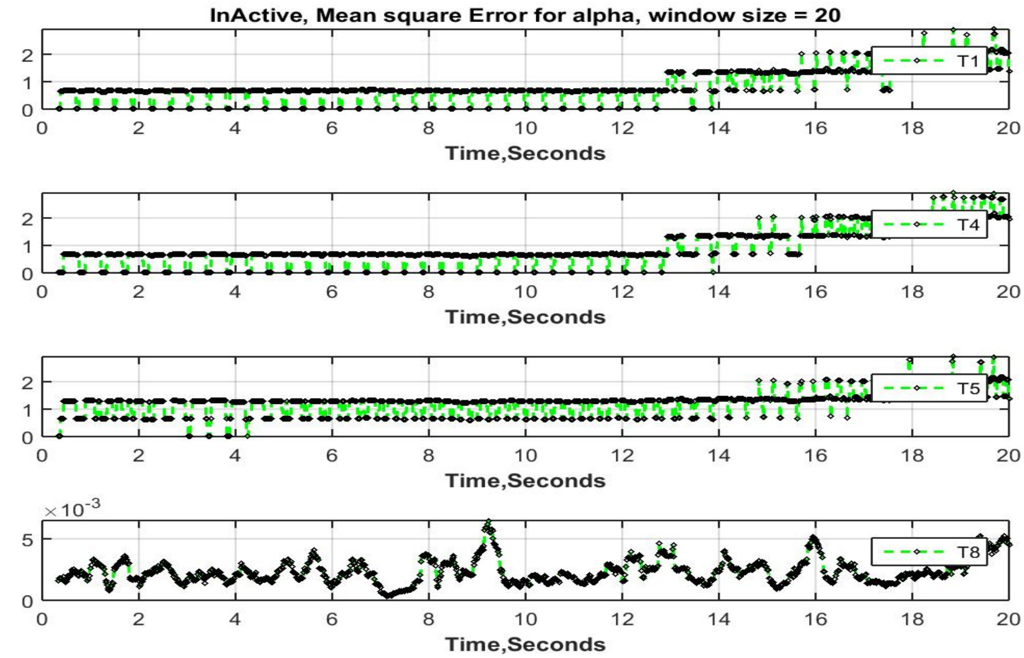
It can be clearly seen that T4 is faulty.

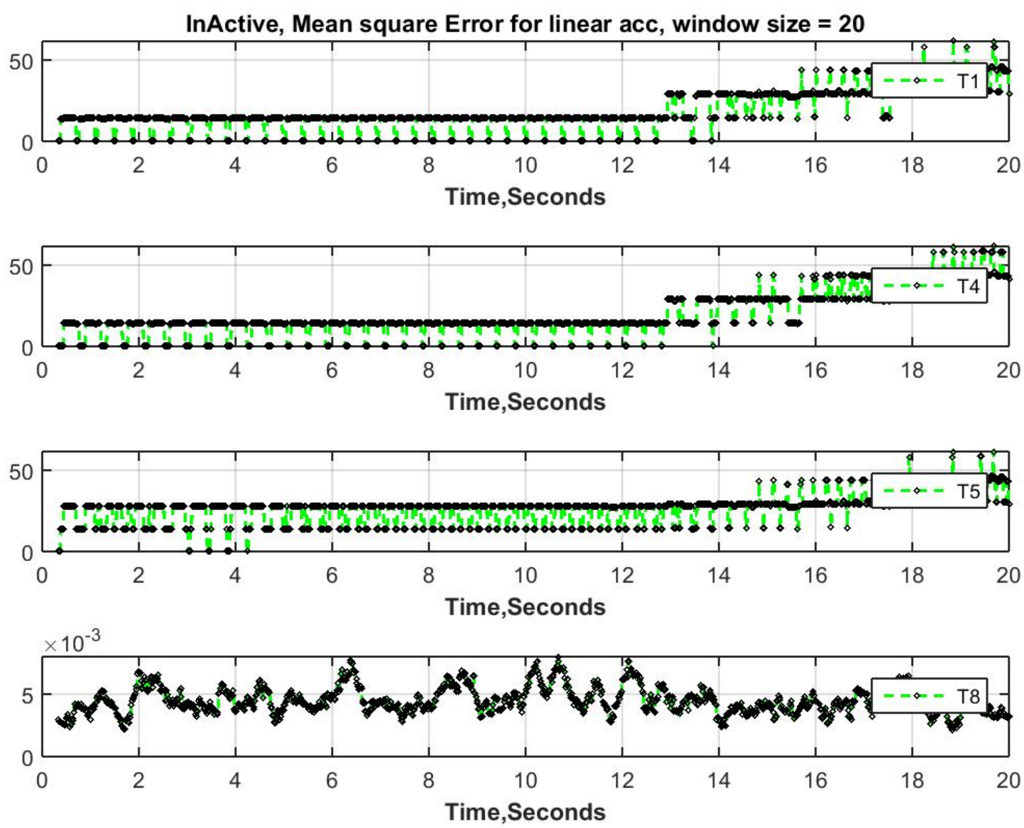
- Active MSE is low for both linear as well as Angular acceleration
- Inactive MSE is low (doesn't have any spikes) for T4 shows there is no measurement error.
- High Inactive MSE for other thrusters shows some other thruster might have failed or may be measurement error. These inference clearly shows T4 has failed.


T1
T4
T5
T8
0
0.5
1
0
2
4
6
8
10
12
14
16
18
20


Active, Mean square Error for alpha, window size = 20
T1
T4
T5
T8
Time,Seconds


Active, Mean square Error for linear acc, window size = 20
T1
T4
T5
T8
Time,Seconds


InActive, Mean square Error for alpha, window size = 20
T1
T4
T5
T8
0
1
2
×10-3
5
0 2 4 6 8 10 12 14 16 18 20
Time,Seconds


InActive, Mean square Error for linear acc, window size = 20
T1
T4
T5
T8
0
50
×10-3
5
0 2 4 6 8 10 12 14 16 18 20
Time,Seconds

1.3.3 Scope for future work

Threshold decision

Decide thresholds

- Threshold_inact_linear,
- Threshold_inact_angular ,
- Threshold_act_linear and
- Threshold_act_angular

Using the tolerance limits of following values:

- Centre of mass estimate
- Mass estimate
- Moment of inertia estimate
- Nominal thrust estimate
- Measurement noise due to estimate of angular acceleration from angular velocity.

Latency

- Refer to [6]

References:

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4. Deyst, J. J. and Deckert, J. C. “Maximum likelihood failure detection techniques applied to the Shuttle RCS jets”
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6. Robust Thruster Fault Diagnosis: Application to the rendezvous phase of the Mars sample return mission.
7. Thruster fault detection, isolation and Accommodation for an autonomous space craft. Robert Fonod, David Henry, Eric Bornschlegl, Catherine Charbonnel.