

## Knowledge-based range safety advisor

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### Abstract

A range safety officer (RSO) monitors in real time the satellite launch vehicle performance to minimise damage likely to be caused in case of failure and destroys it if it deviates from the mission path and is likely to fall on populated areas. The RSO has to correlate interpretations from tracking and telemetry sources by observing various displays. This paper presents a knowledge-based system, range safety advisor (RSA), which attempts to synthesise interpretations from both tracking and telemetry sources and displays the correlated decision and assists the RSO. It employs knowledge from range safety experts, past flight history, nominal data, etc., to infer the vehicle status and presents a comprehensive icon-based graphic screen with the required information and inferences. Visualization is used effectively to design the output screen to convey a very meaningful picture of the vehicle status along with other important parameters. The RSA system is operational and has been tested in real time during the PSLV-D2 launch.

**Keywords:** Knowledge-based systems, real-time expert systems, visualization, mission monitoring of satellite launch vehicle, range safety operation.

### 1. Problem background

The monitoring of a launch vehicle during its ascent is critical and complex in nature. The Range Safety Officer (RSO) monitors the flight and takes decision independently to 'abort' the vehicle if needed. This involves correct interpretation of the data displayed to him/her on various graphic displays/consolas along with the knowledge of the vehicle subsystem and ground-station performance during non-normal conditions.

The flight safety policies are well laid out by various experts involved prior to any mission based on previous flight history, rocket dynamics under various subsystem malfunction, geographical constraints, ground-station performance, etc. For every launch, a set of impact limit lines beyond which significant pieces of the vehicle will not be allowed to impact is established first. The destruct lines/contours are then designed to keep all significant pieces within these lines. The destruct line/contour is defined as the limit at which the malfunctioning vehicle should be destroyed so as to contain all significant fragments resulting from command 'destruction' within the impact limit line. The destruct lines/contours generated are displayed to RSO in the form of plots on graphics workstations. Two types of information are generally used: (i) present position plot, and (ii) instantaneous impact point (IIP) plot. The IIP is the computed impact point

of the rocket at that instant if it is allowed to continue with the thrust cut off. The present position can be displayed in horizontal plane (tangent plane) at the launch site or in the vertical plane along and perpendicular to the launch direction (azimuth). The IIP plot presents the expected impact point trace and the destruct lines. The above plots are drawn prior to launch.

The actual rocket trajectory is plotted in real time (on the plots drawn prior to launch). Presently, RSO employs multiple graphics workstations to display different sources independently. When the strap-on and stage separation events occur, it is possible that the multiple tracking systems track different parts of the vehicle leading to the display of different trajectories on various screens, thereby complicating the decision-making process. Moreover, the performance of launch-vehicle subsystems, which are telemetered from onboard, are projected in separate displays. The onboard vehicle malfunction, which leads to mission failure, and its effect reflected subsequently as trajectory deviation, are displayed separately. RSO has to interpret and correlate the information from these sources by looking into various displays. On the other hand, a range safety advisor (RSA), developed by the Nodal Centre for Expert System at IIT, Madras, and the Mission Analysis and Range Safety Division of the SHAR Centre, ISRO, attempts to synthesise interpretations from both tracking and telemetry sources and displays the correlated decision. It employs knowledge from range safety experts, past flight history, nominal data, etc., for this purpose. The knowledge from the experts is collected in the form of rules and converted into a decision table with some 'heuristics' to resolve certain entries.

The next section presents the knowledge-based system, RSA. Its architecture is covered in Section 3, which is followed by a discussion on the implementation of a prototype version.

## 2. RSA: A knowledge-based system for assisting RSO

The RSA, first of its kind in the Indian space programme, was tested successfully during the launch of PSLV-D2 on October 15, 1994. The RSA is a knowledge-based system to advise RSO during the satellite launch vehicle range safety operation. There have been instances where RSO by virtue of his/her special technical knowledge of the launch vehicle design and dynamics, not executed the 'abort' even under failed conditions\* to give the vehicle time to recover if possible and fly the vehicle under mission salvage mode, or delay 'abort' to acquire valuable data for a few more seconds. The RSA uses such specialised knowledge to infer the vehicle status and presents a comprehensive icon-based graphic screen with all necessary information and inferences required for the RSO.

RSA uses vehicle position data from different sources (tracking and telemetry systems) for inferring vehicle status. Knowledge for inferencing is provided by experts at SHAR, Indian Space Research Organisation (ISRO), in the form of rules. For improving efficiency of real-time inferencing, these rules are converted into a decision table. The

\* Failed condition in this context means that the launch vehicle performance is not as expected.

status of different sources is directly used to calculate an index based on a formula which is used to access a slot in the decision table. Details of internal representation of knowledge and the corresponding inferencing mechanism are presented in the next section. To avoid faulty inference in the case of spurious data, trend-checking is done with a moving window of data.

In order to provide effective communication to the RSO, the output screen was designed using visualization<sup>1</sup>. Meaningful icons and colour schemes were used in place of texts. Vehicle trajectory was displayed to show the deviation and also the stage of the flight. The output screen contains a comprehensive picture of the trajectory and status of the vehicle, health of track sources, and the performance of vehicle parameters. The input data is also archived for future replay which can be used for post-flight analysis.

### 3. The architecture of RSA

The architecture of RSA is shown in Fig. 1. The RSA runs on a PC/AT. The data-acquisition module acquires data in real time through a serial port in an interrupt mode, from mission computers. The data rate on the data bus is 19.2 K bits/s, and the size of one data frame is 100 bytes. The data extraction and preprocessing module extracts and validates each data frame. The data is acquired in an asynchronous way rather than expecting at designated times, as this is required for critical applications like aerospace application<sup>2</sup>. It then generates criteria of deviation for trajectory parameters derived from four radars (two tracking in transponder mode and other two in skin mode), inertial navigation system (INS), and telemetry system. The output from this module is in terms of per cent deviation (except for mission event flags like ignition of the stages, separation, etc.) from nominal values. Any deviation within  $\pm 10\%$  from the nominal value is declared as NORMAL and above it is considered as DEVIATION. Radar not tracking is treated as INVALID. The data-management module archives the pre-processed data and does trend-checking for onboard system parameters. Trend-checking is done to avoid spurious spiky data. Accordingly, a new frame is accepted if its values

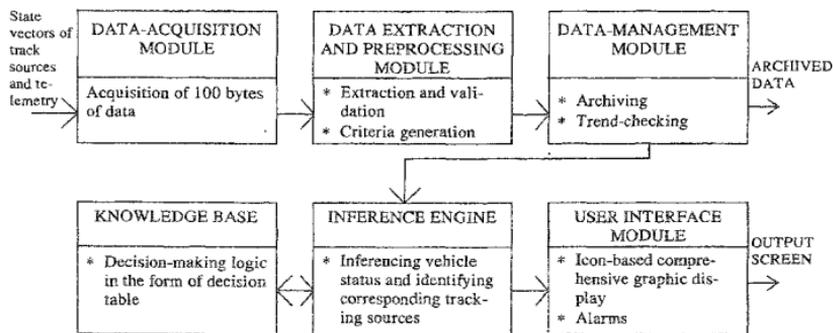


FIG. 1. The architecture of RSA.

are within the  $\pm 5$  times the acceptable nominal deviation. Otherwise, a predicted value based on past 10 frames is used. If there is a data break, the trend-check will be discontinued till the acquisition of three valid consecutive data frames. The output from the data-management module is 'trend-checked' for per cent deviation from nominal value. The inference engine uses this data for inferencing.

The decision logic used, to infer the vehicle status is based on the recommendation of flight safety experts, experience of the range safety group, and the past launch vehicle performance data<sup>3,4</sup>. A simplified logic of decision making<sup>4</sup> is as follows:

*Case 1*

When two or more track sources indicate NORMAL and the others INVALID or DEVIATION, then the vehicle status is NORMAL.

*Case 2*

When only one track source indicates NORMAL and others INVALID or DEVIATION then the vehicle status is NORMAL only if telemetry data is NORMAL.

*Case 3 (When no track sources indicate NORMAL):*

*Case 3a*

When two or more track sources indicate the same DEVIATION, then the vehicle status is DEVIATION with the same value indicated by the track sources.

*Case 3b*

When either only one track source shows DEVIATION and others are not tracking.

OR

When the deviations indicated by the tracking sources are not in agreement, then the vehicle status is NORMAL, only if the telemetry data is NORMAL.

Knowledge for inferencing is provided by experts in terms of rules. For improving efficiency in real-time inferencing, these rules are converted into a decision table. Certain entries in the decision table are resolved using *heuristics*. We have analysed the decision table to extract the following formula which uses the status of different source to directly calculate an index for faster accessing. This upper limit  $(n-1)$  ensures the optimum number of decision table entries.

$$\text{Index} = \sum_{i=0}^{(n-1)} 3^i \cdot A_i$$

where  $n$  = total number of sources and  $A_i$  = status of a source  
{0 : NORMAL; 1 : DEVIATION; 2 : INVALID}

The inferencing procedure works as follows. For example, consider the following two rules:



*Rule 1*

```

IF
Skin_Radar_1 = NORMAL
Skin_Radar_2 = DEVIATION
Transponder_Radar_1 = NORMAL
Transponder_Radar_2 = NORMAL
THEN
Vehicle_Status = NORMAL.

```

*Rule 2*

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IF
Skin_Radar_1 = DEVIATION
Skin_Radar_2 = INVALID
Transponder_Radar_1 = DEVIATION
Transponder_Radar_2 = NORMAL
THEN
Vehicle_Status = H1 (Heuristics 1).

```

Internally, these rules are represented in a decision table. Their index for the decision table is calculated using the index formula mentioned earlier for four sources, as follows:

$$\begin{aligned} \text{Index for rule 1} &= 3^0 \cdot 0 + 3^1 \cdot 1 + 3^2 \cdot 0 + 3^3 \cdot 0 = 3; \\ \text{Index for rule 2} &= 3^0 \cdot 1 + 3^1 \cdot 2 + 3^2 \cdot 1 + 3^3 \cdot 0 = 16. \end{aligned}$$

A portion of the decision table representing these rules is shown in Table I. Heuristics are used to resolve certain entries in the decision table. Internally they are represented as procedures. The H1 heuristics, for example, is as follows:

```

if ( Telemetry = NORMAL) then
    VEHICLE_STATUS = NORMAL
else if ( INS = NORMAL) then
    VEHICLE_STATUS = NORMAL
else
    VEHICLE_STATUS = ABNORMAL

```

The inference engine module uses the vehicle deviation from various track sources and directly finds the index for accessing the corresponding entry in the decision table.

**Table I**  
A portion of the decision table used for inferencing

<i>Index</i>	<i>Skin radar 1</i>	<i>Skin radar 2</i>	<i>Transponder radar 1</i>	<i>Transponder radar 1</i>	<i>Vehicle status</i>
0	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL
1	DEVIATION	NORMAL	NORMAL	NORMAL	NORMAL
2	NORMAL	NORMAL	NORMAL	INVALID	NORMAL
3	NORMAL	DEVIATION	NORMAL	NORMAL	NORMAL
...					
16	DEVIATION	INVALID	DEVIATION	NORMAL	H1
...					



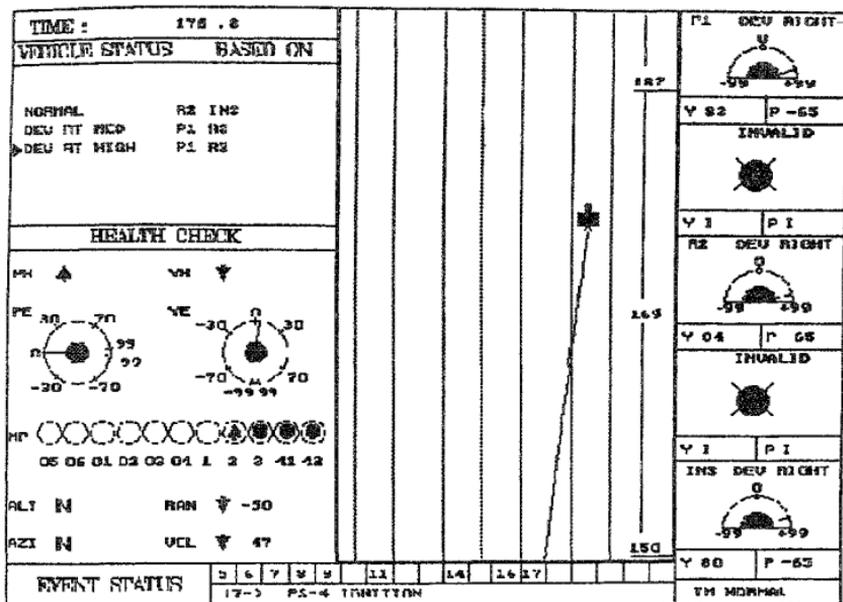


FIG. 3. Output screen from RSA for a simulated anomalous situation.

#### 4. Implementation of the prototype system

The prototype system acquires launch vehicle trajectory data (*viz.*, position, and velocity) from four radars and inertial navigation system (INS), and generates criteria regarding normalcy/deviation, infers the vehicle status, and displays all this information in a comprehensive icon-based screen. This system, which runs on a PC with single-tasking operating system, was developed under C and uses DOS-based interrupt function for real-time data acquisition through a serial port.

##### 4.1. Real-time performance

In real-time systems there is a time budget within which a task has to be completed. In a data acquisition and interpretation system such as the RSA, the software has to acquire the new data (frame), check for errors and do conversion, reason with the data, update the display, archive the data and be ready to receive the next frame. In our case, a data-frame arrives every 200 ms with the volume of 100 bytes in a frame. The time taken for data acquisition and preprocessing is about 70 ms. The time taken for updating the display depends on the amount of incremental change. With the use of icons to improve visualization, display takes between 40 and 48 ms. By using optimum formula for index-

ing the decision table in real-time inferencing, we are able to meet the time budget comfortably using a 66 MHz-486 processor. The average performance of the system is summarised as follows:

#### *Data arrival rate*

100 bytes dataframe @ 19.2 k bits/s, every 200 ms (through a serial port).

#### *Data processing rate*

Data acquisition and preprocessing	60-70 ms
Trend-checking and inferencing	5 ms
Graphic display	40-50 ms
Data logging	5-6 ms
<b>Total</b>	<b>105-131 ms</b>

#### 4.2. Visualization

It is very important to organise the display for effective communication with the RSO. The use of text has to be minimised and icons, colours, highlighting, etc., have to be used to draw the attention of RSO to exceptions and to convey status information. Cluttering of the screen has to be avoided. Further, there is no room to have switchable display in interactive mode which requires action by the RSO. Early attempts tended to increase the text on the screen. Hence, text was displayed iteratively based on its information content and significance and to attract the attention of the RSO.

Figure 4 shows the icons used for display. The sample icons for the vehicle shows the icons used for representing various stages of the rocket. The vehicle icon displayed at any instance on the screen is related to the last event that had occurred. The current stage that is fired is also indicated using the stage number. For the display of onboard parameter, the pitch and yaw errors, a circular dial with a pointer is used. At any instance, a patch of colour at its centre is used to indicate the range of the error. The display of the track sources is similar except that a semicircular dial is used to indicate the yaw deviation value as indicated by a radar. The series of icons for the attitude, propulsion and rate parameters are used to represent the 'normal', 'overperforming', 'underperforming' and 'invalid' states. The last two icons are used only for the propulsion parameters to indicate the full and the burnt-out conditions of the motors.

Cognition effectiveness of the display was increased by visualization as against textual information which would have needed further interpretation by the RSO. Meaningful colour schemes were used: anything in red signifies serious exceptions, while cyan and green represents, respectively, low deviation and normalcy. Visualization has turned out to be so important that one wonders whether one could have implemented a range safety advisor using only alphanumeric display.

#### 5. Conclusions

The RSA was tested extensively with the simulated data before the successful testing in real time during the PSLV-D2 launch. Knowledge used in the RSA was validated by

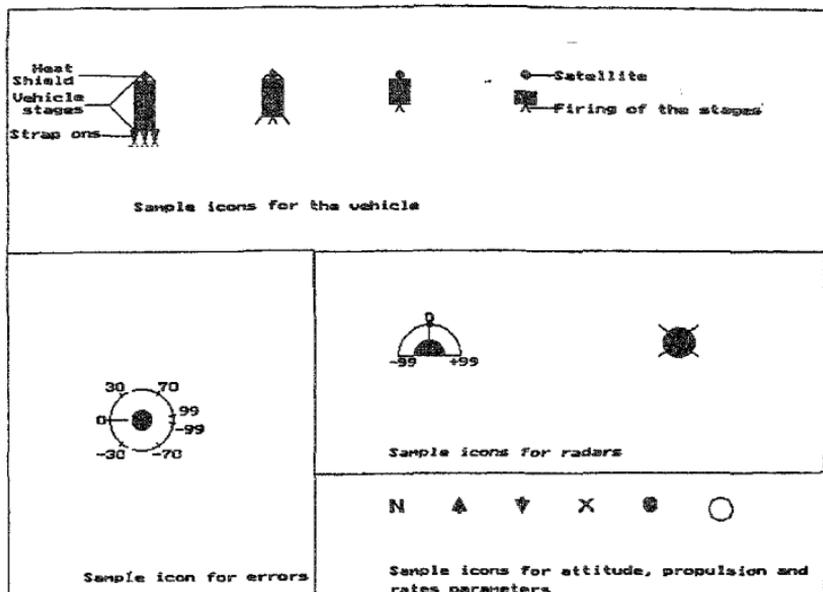


FIG. 4. Sample icons used for display in RSA.

using case-by-case test data. The main advantage of RSA over the existing systems used by RSO is that the RSA employs the knowledge of range safety experts, past flight history, etc., to make a synthesised decision based on both tracking and telemetry systems and displays it on a single comprehensive icon-based output screen. The main constraint on the real-time processing was met satisfactorily by using a powerful processor, and an optimal formula for indexing the decision table for inferencing. Visualization was used effectively to design the output screen to convey more meaningful picture of the vehicle status along with other necessary information.

Fine-tuning the RSA is a continuous process based on feedback on its use in successive launches. Presently, an automatic report-generation module is being developed as an extension to the existing system.

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## References

1. Special issue on visualization, *IEEE Computer*, 1994, 27, No. 7.
2. PRASAD, B. E., PERRAJU, T. S., UMA, G. AND UMARANI, P. An expert system shell for aerospace applications, *IEEE Expert*, 1994, 9, 56-64.
3. SANKAR, S., KRISHNAMURTHY, V., BALAKRISHNAN, S. S. AND JANAKIRAMAN, R. *Range safety real-time expert system for launch vehicle: RANGER* Report No. 1, MARS & IREX, SHAR Centre, ISRO, February 1991.
4. JANAKIRAMAN, R., KRISHNAMURTHY, V. AND SANKAR, S. *Range safety real-time expert system for launch vehicle: RANGER* Report No. 2, MARS & IREX, SHAR Centre, ISRO, October 1991.
5. KAO, S., LAFFEY, T., SCHMIDT, J., READ, J., AND DUNHAM, L. Real-time analysis of telemetry data. In *Third Annual Expert Systems in Government Conf.: Proc.*, (H. J. Antonisse, J. W. Benoit, and B. G. Silverman (eds.)), IEEE Computer Society Press, 1987, pp.137-144.