Abstract. This paper discusses a practical approach to simulating the ejection of the crew module from the F-111C aircraft, using the F-111C Mission Simulator in service with the Royal Australian Air Force (RAAF). Exact replication of such a dramatic and complex event is virtually impossible, therefore the prime objective was to model the key events and functionality that provide a solution of training value to RAAF aircrew. Most requirements focussed on ensuring the simulator cockpit control functionality is identical to the aircraft, such that aircrew procedural check lists may be followed and executed for both regular and alternate ejection cases. Also of importance was modelling the crew module and parachute dynamics, such that the simulation produces realistic recovery trajectories as perceived from within the cockpit and according to parametric plots.

A number of considerations made the task of simulating the crew module ejection more challenging. The design and testing were hampered by the absence of adequate aerodynamic and trajectory data, the wide envelope of airspeeds/attitudes within which the aircrew may eject and selection of a suitable parachute model.

The paper discusses how these issues were resolved, and explains the methodology used to create the model and integrate it into the simulator. The paper also discusses how the ejection simulation is used in training and the perceived benefits of its use.

1. INTRODUCTION
In 1993, Thales Training & Simulation (then Wormald Technology) was awarded a contract to replace an existing F-111C Mission Simulator with a training device which simulates the performance and function of the RAAF's post-AUP (Avionics Update Program) aircraft.

The post-AUP F-111C Mission Simulator was installed at RAAF Base Amberley in 1997 as an interim fit for the previous simulator. In December 2000 the F-111C Mission Simulator underwent final acceptance by the Commonwealth of Australia. It has been operated and maintained by Thales Training & Simulation since installation.

Designed and constructed in Australia, and powered by over 40 computer processors, the simulator delivers realism in the out-the-window and Pave Tack Infrared image, Digital RADAR Landmass Simulation (DRLMS) of both Attack and Terrain-Following Radars, high fidelity Weapons Simulation and integrated Electronic Warfare Simulation. The F-111C Mission Simulator is considered one of the most sophisticated and complex simulator devices in Australia.

As part of on-going support to 82 Wing, Thales Training & Simulation provides instructional support through two Qualified Flight Instructors (QFIs). The QFIs not only provide instructional support to 82 Wing's 1 SQN and 6 SQN, they also fly F-111 aircraft as RAAF reservists and provide constant engineering feedback to the simulator design team.

Working with the design team, the QFIs identified a training need to provide realistic post-ejection training to condition aircrew in the event of an actual ejection. This paper explores the challenges of providing a simulation of the crew module from the point of ejection.

1.1 Ejection Simulation
The F-111 is one of the few aircraft capable of ejecting the entire crew module in case of emergency. Following ejection of the crew module, certain procedures must be followed to increase the probability of a safe landing. The RAAF F-111C Mission Simulator functionality had to be upgraded to provide this training capability.

There were two major tasks to accomplish: firstly, to simulate the behaviour of the equipment in the cockpit including aural and visual effects, and secondly, to adequately represent the motion of the ejected module. Adequacy of the model dynamics may be objectively evaluated against limited published test data. The model may also be assessed against subjective criteria, such as the “perceived realism” of the visual scene displayed on a $150^\circ \times 50^\circ$ field-of-view screen. Reproducing the response of the cockpit instrumentation was relatively easy, while simulation of the crew module motion presented a non-trivial challenge.

2. PROBLEM DESCRIPTION

2.1 Requirements
One of the core requirements of the simulation was simply formulated as:

“The contractor shall develop a flight dynamic model of the crew module that will generally represent the ejection trajectory defined in the F-111C AUP Flight Manual” [1].
The requirement links the dynamic performance to the graph shown in Figure 1. This illustrates the relationship between the vertical flight profile and the main events that occur following ejection and during the descent. The correlation of these events and the crew module’s trajectory with time thus requires realistic dynamic representation.

The practical requirement is to give trainees the opportunity to exercise emergency procedures within a simulated environment. This requires realistic and timely behaviour of the:

- cockpit instruments;
- aural cues (loss of intercom, sound of rocket motor, parachute deployment, crew module repositioning);
- proprioceptive cues (seat bump due to rocket motor, loss of hydraulic power to control stick and rudder pedals, crew member repositioning by nitrogen powered inertia reels); and
- visual scene.

These correspond to the key events in the ejection sequence.

The simulation must be capable of providing recovery from a wide range of ejection conditions, including low level, high speed, inverted flight. This presented significant modelling challenges, since there is a wide range of permutations of roll angle, pitch angle, airspeed and terrain height that fall within the published ejection envelope [1].

- Simulation had to be in real time with a time step not smaller than 1/60 second;
- The processing time not to exceed 1/300 second;
- A complete set of aerodynamic parameters for the wingless crew module were unavailable;
- No readily available mathematical model of the stabilisation-brake or recovery parachutes; and
- Limited time and budget.

Available parachute models tend to be either too simplistic or overly complex (such as those that require solution of the Navier-Stokes equations). Therefore an intermediate model had to be developed independently and from first principles.

The F-111C Mission Simulator Ownship dynamic model is a standard non-linear, 6 Degree of Freedom (DOF) model solved in real time using an explicit Euler integration method. This model had to be retained while eliminating the contribution of the aircraft body that separates from the crew module after ejection. However the challenges of achieving real time performance proved the most limiting constraint. Multibody numerical models are notorious for their high numerical instability and significant demand for processing power.

2.3 General Assumptions

The ejection has several stages where the recovery parachute does not play a significant role. The assumptions below only apply to recovery parachute-crew module interaction. A discussion of the powered phase of the flight is not within the scope of this paper.

1. Due to high mass-surface ratio of the crew module, aerodynamic data can be estimated without risk of major errors.

2. The only action of the parachute on the crew module is through a force acting on a single confluence point, thus affecting the module when the line is stretched. The force acts along a single line connected to the centre of the parachute. The line cannot wrap around the crew module.

3. The recovery parachute is modelled as a closed hemisphere containing some volume of air comparable to that in the open dome. The chute can translate in 3 dimensions subject to gravity and drag forces, and the tension exerted by the crew module (when the line is stretched).

4. Given the assumption of a closed hemisphere parachute model, it is further assumed that the associated drag force acts through the centre of gravity.

5. Parachute inflation is be modelled using an arbitrary function that steadily increases the size of the stabilising mass over a known time period in an asymptotic manner.

Figure 1 F-111C Crew Module Ejection Sequence (Typical Low Speed Ejection) [1]
3. MODEL DESCRIPTION

The recovery chute – crew module system is modelled as two distinct bodies, each with their own equations of motion, constrained by an adjoining elastic line. According to established engineering practise, analysis focussed on developing the simplest possible solution meeting the stated requirements. Preliminary modelling simulated the motion of the crew module only, representing the recovery chute as a variable force vector. This approach provided satisfactory results for low speed, wings-level test cases. However the model could not provide recovery from initial conditions with higher speeds and/or abnormal attitudes. This indicated the need for a more sophisticated model. Further analysis demonstrated the importance of the interaction between the recovery chute and the crew module, in order to recover from initial conditions closer to the edges of the ejection envelope, where survival is still expected.

4. MATHEMATICAL MODEL

4.1 Coordinate System

The interaction between the crew module and parachute is resolved in the Cartesian North-East-Down (NED) Earth frame coordinate system, with the origin located at 0ft altitude (WGS-84).

4.2 Equations of Motion

The general set of equations of motion of the parachute-lines-crew module system can be presented in a compact form as follows:

\[
\begin{align*}
m_p(t) \frac{\partial \vec{v}_{Ep}(t)}{\partial t} &= \vec{F}_{Ed} + m_p(t) \vec{g} + \vec{F}_{Eb} - \vec{F}_{Et} \\
\frac{\partial \vec{v}_{Ba}(t)}{\partial t} &= Y \left( R \times \left( \vec{g} + \vec{F}_{Et} \right) , \vec{F}_a \right) \\
\end{align*}
\]

where:

- \( m_p \) - mass of the parachute including some estimate of air mass permanently enclosed.
- \( \vec{v}_{Ep} \) - parachute velocity vector NED.
- \( \vec{F}_{Ed} \) - estimated drag force vector resisting parachute motion NED.
- \( \vec{g} \) - gravity acceleration NED.
- \( \vec{F}_{Eb} \) - buoyancy force NED.
- \( \vec{F}_{Et} \) - tension force of the stretched line NED.
- \( \vec{F}_a \) - resultant vector due the sum aerodynamic, propulsion forces acting on the crew module NED
- \( \vec{v}_{Ba} \) - crew module velocity vector in body frame.
- \( Y \) - a symbolic representation of the 6 DOF aircraft/crew module force equations.
- \( R \) - Rotation matrix from NED to aircraft body axes.

Discussion of these parameters are presented below.

The first equation describes 3 DOF parachute dynamics in earth axes, while the second equation is a symbolic representation of force equations.

The abbreviated form shows how the two dynamic subsystems are tightly coupled via the tension force of the “string”, \( \vec{F}_{Et} \).

In summary, this is a non-linear two body simulation problem with one body represented with 6 DOF and the other with 3 DOF.

4.3 “The Two Body Challenge”

Although multibody equations of motion are not a novelty, they present a serious practical problem given the constraints mentioned above.

Stiff Ordinary Differential Equation (ODE) methods (such as Gear [3]) that may provide accurate integration results, are time-consuming and time-unpredictable. According to [4], they do not adjust well to discontinuities that may be expected when the parachute line transitions between stretched and relaxed states.

Additionally, strong coupling and possible stiffness of the system would require a complete re-write of the aircraft model to change from sequential (time-step) integration to a more complicated scheme. Time and budget resources definitely ruled out this approach.
Given that significant amounts of data were unavailable, it became clear that compromising theoretical integration accuracy for a reasonable and stable working model within the budget is a satisfactory trade-off.

The difficulties associated with equation-coupling were overcome by recognising the elasticity of the line. Once a degree of elasticity is assumed, Hooke’s Law can be used to determine the resulting tension force using the distance between the parachute and the mount point on the crew module. The coupling then disappears and there is no formal obstacle to using the explicit Euler method. With a sufficiently high Hooke Constant, one may expect convergence of the approximate solution to the ideal one. Accuracy and stability cannot be predicted from theoretical consideration as a result the inherent complexity of the crew module and a relatively large time-step. Implementation of this concept was relatively simple, so the model could be verified and tuned experimentally.

Having presented the approach, a detailed description of parachute model parameters can be made.

4.4 Tension Force $\vec{F}_{Et}$

To account for discontinuities that may occur when the lines are not stretched, the formula for the tension force is:

$$\vec{F}_{Et} = k \cdot \text{Heaviside}(D - L) \cdot \begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix}$$

where:

$D$ is the current distance of the parachute centre from the chute line’s mount point on the crew module.

$L$ is the length of the chute line when tension approaches zero.

$r_x$, $r_y$, $r_z$ are coordinates of a displacement vector which is oriented along the stretched line, and has the magnitude of the increased length due to interaction of the two bodies.

These coordinates are functions of the geometrical positions of the two bodies and $L$.

The Heaviside function relaxes the tension force if two bodies become too close.

A reasonable value of the Hooke constant, $k$, was determined from analysis of numerical stability of the two body system.

When the line is sufficiently inelastic, the set of equations become numerically unstable, as expected for the case of coupled equations. The consequences of introducing an elastic line have been verified.

During the early stages of flight when extreme tension forces are generated, the line may extend to twice its relaxed length (for the $k$ that ensures stability of the Euler integration). The overall error is minor when compared to an accurate solution obtained using the Gear method with $k$ 10 times greater, where line extends only by ~11% as shown in Figure 3.

4.5 Mass of the Parachute $m_p$

The mass of the parachute is assumed to consist of the harness, canopy and some representative mass of the air enclosed. Since there is no chance of true parachute simulation to assess the nature of acting forces, a conceptually simpler balloon-like model is assumed.

Since some inflation period is expected, the mass is assumed to change in accordance with equation:

$$m_p = m_0 + \rho \cdot V(t)$$

where:

$m_0$ is the mass of the harness and fabric.

$\rho$ is the local air density.

$V(t)$ is the current volume based on some inflation time profile.

4.6 Drag Force $\vec{F}_{Ed}$

Drag force is calculated as:

$$\vec{F}_{Ed} = -C_d \frac{1}{2} \rho \cdot \begin{bmatrix} V_n \cdot \sqrt{V_n^2 + V_e^2 + V_d^2} \\ V_e \cdot \sqrt{V_n^2 + V_e^2 + V_d^2} \\ V_d \cdot \sqrt{V_n^2 + V_e^2 + V_d^2} \end{bmatrix} \cdot E(t)$$

where:

$\rho$ is the local air density.

$v_n$, $v_e$, $v_d$ are the parachute velocity vector components North, East, Down respectively.

$C_d$ is the drag coefficient (including reference surface area).

$E(t)$ is an inflation scaling function described later.
The value of the drag coefficient is calculated using the known equilibrium descent rate of the crew module.

4.7 Buoyancy Force $\vec{F}_{eb}$

This force has very little effect during the steady state descent, however it may be significant during the initial stage of chute deployment to achieve separation between the inflating parachute and the crew module descending under gravitational force.

4.8 Inflation Model

Based on available documentation, it has been deduced that the inflation is largely completed within 4-6 seconds. An arbitrary function matching the uncertainty of such a statement was adopted. Its typical profile is shown in Figure 4.

The corresponding equation is:

$$ E(t) = \text{Heaviside}(t - t_0) \left\{ 1 - e^{-e^{\left(\frac{t-t_0}{t_0}\right)^3}} \right\} $$

where:

- $t$ is the time since ejection and
- $t_0$ is time delay from ejection to parachute deployment.

The variable volume then can be described as

$$ V(t) = \frac{2}{3} \pi r^3 E(t) $$

where:

- $r$ is the radius of the parachute when fully inflated.

5. MODEL IMPLEMENTATION

5.1 Prototyping

Preliminary derivation and validation of the concept was performed with the Maple Algebra Package using a second point mass 3 DOF body as an approximation of the crew module. Numerical integration of the system of equations using the Euler method gave stable results within the expected ejection envelope. This provided sufficient confidence that the model would meet the requirements of the task. The prototyping phase ended with all validated equations and approximated values of physical parameters. The model was then ported to real-time software modules, where the crew module was represented with 6 DOF.

5.2 Integration

The primary challenges associated with integration of the ejection model related to tuning of the flight model to achieve satisfactory visual effects, for initial conditions across the entire ejection envelope. This work could only be performed on the Simulator and was based on feedback from the QFIs.

6. CREW TRAINING PERSPECTIVE

Historically, F-111 ejections inevitably result in crews sustaining spinal injuries to the thoracic region of the spine. These injuries are classically F-111-specific and are a result of the significant g forces sustained on landing rather than during the ‘relatively gentle’ module separation.

Optimum aircrew posture for ejection is easily achieved with minimal warning as the ‘normal’ seat pan and strap configuration used in flight supports the upright posture recommended.

The recommended posture for landing however requires both seat pan and rudder pedal adjustments to minimise upper body rotation upon ground (or water) impact.

Training aircrew to achieve this posture is a safety critical event included as a formal part of initial F-111 aircrew qualification. It is also assessed regularly as part of Squadron simulator mission training.

The ejection simulation in the F-111 Mission Simulator originally froze all activity at the point of activating the ejection sequence and recorded the parameters to assess survivability. Crew training for the critical post ejection reconfiguration of the seat/rudder adjustments was achieved ‘out of scenario’ and was a fairly academic exercise. Anecdotal evidence suggested that the achievement of this posture adjustment was, in fact, quite difficult following the disorientation of the ejection and compression of time available in steady descent after completion of the module ejection sequence. This was particularly the case at low level where the majority of F-111 operational training takes place.
The modelling of the post ejection sequence has injected realistic visual, proprioceptive and aural cues to aircrew. Of particular value to training for post ejection survival the crew is presented with the initial disorientation of module separation and reposition, followed by visual indications of the high rate of descent to impact. The total timeline for the required actions is available to train against.

As an example, in the worst case, a runway ejection takes some 15 seconds from ejection initiation to module impact. The first 9 seconds are not available to crews as a result of module separation and repositioning under the parachute, leaving just 6 seconds to achieve the desired posture adjustment. Prior to the post ejection simulation, the time criticality of this scenario was unable to be presented to trainees.

7. CONCLUSION

The task of simulating ejection of the crew module presented a greater challenge than first anticipated. Despite this, an effective solution was developed within significant constraints through careful analysis incorporating appropriate compromises. Crews can now train to complete critical safety events in a representative timeline with significant increase in training validity and value.

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REFERENCES

2. “Predicted Flight Characteristics of the Crew Module” (F-111A/B), General Dynamics, Fort Worth Division, Report A394, 22 April 1968.