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Development of an Approach that Delivers a High-Tempo of High Speed Flight Trials at Affordable Costs.

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Abstract

Although the Australian flight programs HyShot, HyCAUSE and HIFiRE successfully achieved hypersonic flight testing at a third of the cost of the typical flight program at the time, to successfully demonstrate components and systems applicable to high speed flight, a high tempo of demonstrations that can be achieved at even lower costs needs to be possible. In addition, a pipeline of talent to continue to specifically support flight demonstrations and ultimately development of marketable systems needs to be established. At the University of Queensland, the challenge of developing such an approach has been undertaken. A flight program, STAje-, was initiated to demonstrate high speed electric propulsion, but also to meet this challenge. This presentation provides details of the approach that has evolved. It includes a description of the approach to payload development and manufacture, as well as rocket motor design and the importance of an independent range with land recovery.

Keywords: *Flight Testing, High-tempo, Affordable*

Nomenclature

COTS – Commercial-off-the-shelf

AM – Additive Manufacturing

LORA – Long Range WIFI

G&C – Guidance and control

RDT&E Research Development Test and Evaluation

1. Introduction

With transition of high-speed flight into operational systems, there has been the realisation by the end users that modification and testing new high-speed concepts is both costly and time consuming. Hence, there has been calls from multiple agencies for the high-speed flight community to develop an approach to increase the frequency of testing by an order of magnitude and at reduced costs. The US based JHTO even offer a prize to US citizens who could come up with a concept.

Australia has a long history in hypersonic design, testing and flight trials. Unlike in most countries where hypersonics RDT&E was a Defence-driven effort, Australia's Defence hypersonic program commenced due to the success of *University-based* hypersonic fight testing. This resulted in developing very cost-effective processes and procedures to undertake hypersonics RDT&E using sub-scale vehicles. An example of this was the many flights of HyShot, HyCAUSE and HIFiRE. The hardware and effort were approximately a third of that for similar programs undertaken in the USA and at the same time, achieved a similar success rate. However, although this was an accomplishment at the time, it fails to meet the current ambition for tempo and costs. To place this in context and to build on it, it is important to realise that HIFiRE did not have at its disposal suitable COTS hardware and software, nor effective additive manufacturing. The range was not an issue nor was the rocket motor as costs and frequency of flights were not major constraints.

A cost breakdown of a flight trial very quickly demonstrates the majority of the costs are in the wages of the people involved in the program. Hence, to first order, methodologies to reduce this cost are required. If this is coupled with a high tempo requirement, then a solution is to reduce the time taken by the team to develop and implement a flight. Essentially, this equates to reducing the constraints to developing a suitable flight. In hypersonic flight testing there are many constraints, and the time spent by the flight team meeting these constraints is the bulk of the costs. Tunnel testing is cheaper, not just because rocket motors are not used (mostly), but because a ground test program is less constrained.

The HIFiRE approach has now been modernised in the STAje- flight program. Although it aims to demonstrate the capabilities of a novel high-speed electric propulsion system, due to financial constraints, it became necessary to explore modern design, manufacturing and implementation approaches to achieve this objective. Thus, serendipitously, the objectives for low-cost high-speed flight experiments has been achieved. The high tempo has not been demonstrated to date, but the path forward is clear.

2. Flight Module

The approach is predicated by the assumption that testing will be achieved by first boosting a payload to the desired altitude and velocity with a rocket motor and the system as a whole is not reusable.

Table 1 provides an approximate cost breakdown of a traditional low-cost flight program which lasts 3 years. It is clear that the majority of the costs are on personal, though some direct cost savings are potentially available on the rocket motor system and the cost of engaging the range. The payload in itself is a small value, however, the design and manufacturing approach influences the time spent developing it, thus it has a major impact on the overall cost.

Although not apparent at first, bespoke manufacture of rocket motors and the availability of a dedicated range also has an impact on the time consumed on the payload development and flight frequency. Hence, although direct cost reductions in this area are desirable, it is actually their impact on the payload design which is more important.

Table 1. *Cost breakdown of a traditional flight campaign*

Activity	Approx. Cost	Note	Percentage of overall cost
Payload hardware and manufacture	\$0.6M	Depending on complexity	4%
Rocket Motor System	\$1.5-\$3M	Motors, fin sets certification, engineering and trajectory dependant	12%
Range	\$0.75M		5%
Program Management	\$1M	2 people for 3 years.	6%
Technical Team	\$12M	20 people for 3 years, wages and on-costs	73%
Total	\$16M		

At the University of Queensland, we have reduced costs and it is expected that the frequency of testing will increase by addressing five inter-related aspects associated with flight testing:

- Flight Regime
- Payload Design and Manufacture
- Rocket Motor System
- Range
- Management

3. Flight Regime

For a significant portion of requested hypersonic testing, it is unnecessary to test at exactly the same flight speed, altitude, etc that the item being tested will ultimately be implemented at. The majority of the effort to gain confidence in a capability or theory can be completed at lower speed, albeit from a theoretical standpoint, it most likely should be tested at supersonic speeds. Tunnel experimenters do this regularly. For example, to observe viscous related phenomena, Reynolds number will be matched to the actual flight conditions even though the velocity may not.

A practical example of this approach was demonstrated in HIFiRE 5. This hypersonic flight test was developed to measure natural boundary layer transition over a cone and correlate it with theoretical predictions. Unfortunately, the second stage rocket motor failed to ignite and although the flight was supersonic, it was not hypersonic and the altitude was significantly different. Notwithstanding, the results of the measured boundary layer transition location were consistent with theoretical predictions for the achieved trajectory. More importantly, if they had not been, then this would have had serious implications for funding a repeat hypersonic flight.

Thus, one approach to reduce costs is to incrementally build on less expensive low speed flights towards the higher speed and presumably more complex flight. These hypersonic flights would occur less frequently and would potentially use a more classified environment. The lower speed testing is a very fruitful step between ground testing and a full-scale hypersonic flight test. Because they are easier to implement they can be exploited to produce a high tempo of flights.

Breaking the development path into a series of **high tempo flight trials** lends itself to:

- **an incremental development path** of technology that reduces risk by providing off ramps;
- increased opportunities to develop **alternative technologies**; and
- opportunities to **develop a pipeline of expertise.**

This contrasts strongly to completing a limited number of high-profile, high-cost flight demonstrations.

Quantitatively, the approach being developed at the University of Queensland implements the following broad requirements:

- **Mach 3-5** flights are being conducted to allow most of the testing relevant to the hypersonic flight regime to proceed:
    - Rapidly;
    - with significant flexibility; and
    - in general, with a signal rocket motor, which significantly reduces costs and complexity.

- T**he apogee is restricted** to approximately 40km to reduce the extent of the safety template and provide greater opportunities. Although the heart of HyShot, HyCAUSE and HIFiRE was the up and over trajectory which was shown to be cost effective to implement, at the lower speeds, direct insertion is also within reach at a similar cost. This opens the door to a much wider range of experiments and is more applicable to an operational system.

- **Controlled trajectories** should be implemented, albeit, this is not the case at present. The majority of the experimental hypersonic flight tests use unguided spinning rockets, of multiple stages. Range safety are familiar with this approach. However, it was born at a time when G&C was not practical for a low-cost mission. This has changed. G&C is now readily available in small low-cost packages. The barrier to their implementation is actually the conservative reaction of the range. They rightly have concerns, because they can imagine scenarios of very energetic low-cost systems which don't work out well. However, with lower energetic trajectories, these low-cost systems can be demonstrated safely. If this capability is developed, this reduces the mechanical and thermal loads on the payload, as well as offers experimenters with new options.

It also reduces the cost and time developing a flight vehicle, because the experiment test window is no longer constrained to fit within a gravity turn.

4. Payload Design and Manufacture

To achieve reduced costs and a high tempo, a universal test bed could be implemented and is indeed a potential solution which will be available in Phase 2 of STAje-. A number of teams are also following this approach. However, the HIFiRE experience demonstrated that many different constraints are often incurred to meet the scientific requirements of a flight. These constraints often take a design team down a path to develop a specific vehicle for the task. This has traditionally been time consuming, which is why a universal test bed is preferred as a partial solution. However, bespoke development of payloads (or modification to test beds) can now be achieved in a short time frame and with reduced costs by implementing the following modern approach:

- **COTS hardware and software** are used where possible;
- **Additive Manufacturing** (AM) is embraced;
- **A wooden round** designed to enable deployment to the range with minimal integration and the need for last-minute qualification; and
- **The lower energy flight regime** discussed above**.**

This approach to payload design and manufacture has been widely discussed but because flight programs are expensive and payload costs are not the major contributing factor, designers will simply implement the best line replacement units and buy the ultimate machined hardware. However, the difference is that the traditional approach requires the design to be perfect, because significant time is otherwise required if a new part has to be manufactured. Hence, the design effort drives the costs. By implementing AM, errors can be tolerated because design changes can be accommodated in a timely manner, especially if in-house AM is possible. The printers operate continually and new complex parts can be manufactured in a very timely manner. Furthermore, these errors are not time waisted as they more often than not lead to more advanced understandings that results in less conservative designs which provide new opportunities to solve longstanding problems. Figs. 1 and 2 provide an example of this approach implemented in the STAje- payload design and flight hardware, respectively.

In addition, in many applications, COTS hardware can be implemented. These systems come with major support and a solid basis from which detailed software can be developed with a basic engineering (or less) degree, whereas bespoke hardware does not and requires specialists to implement it.

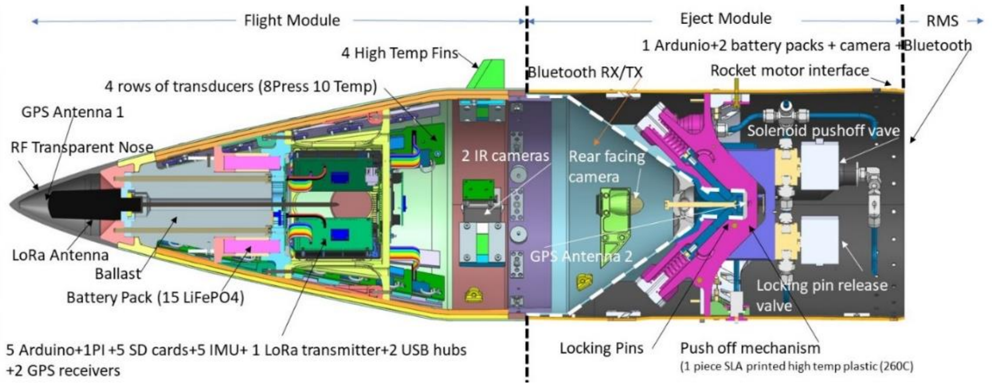

Figure 1. *STAJe- Phase 1 flight payload which implemented COTS hardware for all line replacement units, AM manufactured bulkheads which took advantage of the complexity which is possible with this approach, and payload shells that have the potential to be mass produced.*

Undertaking flight testing at lower flight speeds, the heating loads become significantly more manageable. This lifts the design constraints considerably. In the hypersonic regime, the payload is typically designed to meet the heating loads which generally results in considerable design effort to manage. The mechanical loads are generally satisfied as a result. At the lower Mach numbers this becomes less so. Generally speaking, satisfying the mechanical loads is usually sufficient to satisfy the heating loads. The mechanical loads are more well defined, so they are easier to design too and a wider choice of materials is available. Furthermore, because the flight regime is less energetic, for most accessible rocket motors, there is more margin on payload weight and thus less constraint on the designer to meet strict weight budgets. This means, simple designs can be implemented which have large safety factors. In addition, excessive, detailed studies to verify a design are not required, thus saving significant time initially. However, it is still not agricultural, and specialised knowledge is required.

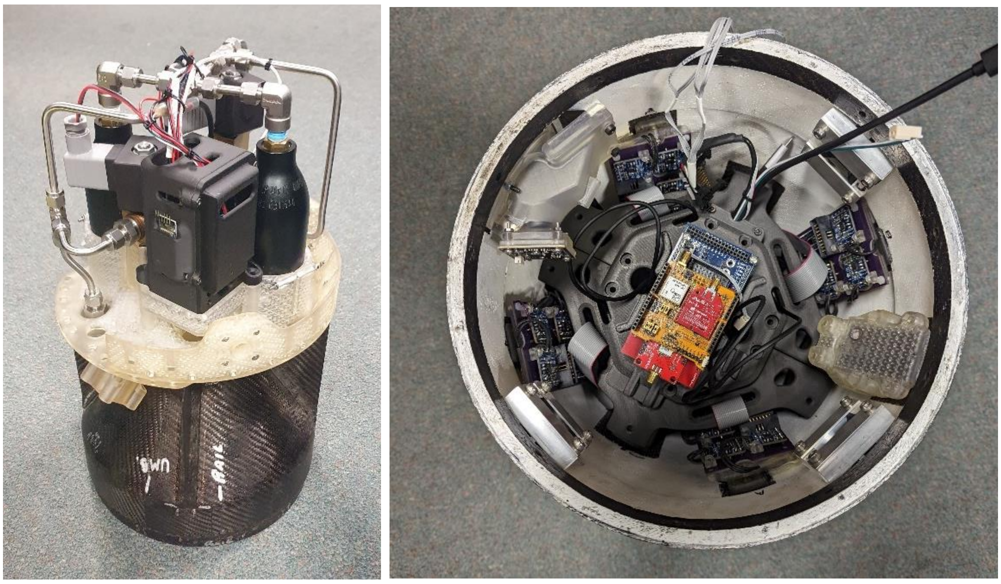

Figure 2. *Payload Eject Module (left) and looking forward into the front section of the Flight Module (right). The extensive use of additive manufacturing and the integration of COTS hardware can be seen in both pictures.*

5. Rocket Motor System

Currently, there are only a limited number of different rocket motors available to the community to undertake flight testing. Hence, the design of any payload is heavily constrained by the performance characteristics of those rocket motors. It should not be underestimated the extensive time required to meet both the stability requirements necessary for the flight and the performance requirements demanded by the scientific requirements. This can take months. Hence, to develop a high tempo of flights with payloads that will meet the usually very specific scientific requirements, bespoke motors, moreover a class of motor with widely adjustable performance that is tuned to meet the scientific requirements, is required.

It is appreciated that this is a significant shift from the current approach. However, solid rockets that have bespoke casings, typically wound using carbon fibre, are now possible. They can be tailored to the required flight by changing the motor's:

- Diameter;
- Length;
- Throat diameter; and
- Propellant constitution; and
- Incorporating control surfaces and thrust argumentation to allow for controlled flights.

A traditional rocket motor developer will point to the very time-consuming process of certification to ensure reliability etc, which makes this approach impractical. However, once the material choices have been made and demonstrated to be acceptable, and furthermore, a solid understanding of the loads is known, then for the purpose at hand, extensive certification is not required. However, a risk to the mission exists with each change and even in the potential for variation in manufacture. That needs to be accepted, although it should be mitigated with a test firing where the change is significant.

STAJe- is implementing this approach and the University is winding casings and the nozzle casing for a local solid motor manufacturer, BlackSky Aerospace, to develop such a motor for STAJe-. This was required, because the payload only ways 26kg and repurposed certified motors accelerated the payload to Mach 5 at 10km or less, which places unacceptable loads on the payload, actually defeating the purpose for flying at lower speeds. A slower burn was needed to insert at higher altitudes and slower speeds, and as a result a fatter and shorter motor is in its final stage of development to meet the requirements of the flight program.

6. Range

Most ranges suitable for testing high-speed systems are oversubscribed. This is not conducive to a sustained high tempo of flight testing. It is clear that a new range dedicated to high speed flight is required. Australia is a vast continent, with low population, hence from a safety perspective, there are multiple options available to develop a new range. Notwithstanding, additional cultural and environmental issues still need addressing. However, the University of Queensland has been developing approaches to enable development of a new range conducive to low cost sustained tempo testing. This is being achieved by:

- **Developing a dedicated private land-based range** that implements modern low-cost and to some extent more reliable technology;
- An increased focus on **standardisation of range** infrastructure, utilisation and operations, and
- **Standardised safety templates** (made possible because of the flight regime) to improve safety and certification workflows.

It is appreciated that there could be scepticism that this approach could be made operational, so the University of Queensland, under its STAje- program, has demonstrated that such a range could be developed. Fig. 3 is an aerial picture of the region chosen to make the demonstration. It consists of:

- flat land that is essentially clear of vegetation, which would be used to launch the vehicle from. This region is approximately 20km x12km and is to be used for payload and motor recovery;
- a ground control station (Fig. 4) is located 1km behind the launch area;
- hills located 32km down range along which are multiple fixed receivers (Fig. 5), that implement LORA (Long Range WIFI) for receiving data from the payload and communication with the ground control station;
- communication with the nearest town (50km away) to allow access to the internet and control of many aspects of the launch remotely;
- multiple low cost methodologies to track the flight vehicle, avoiding the use of GPS, though it is debatable if it is more cost effective to employ an unrestricted GPS; and
- power supplied to all sites by solar energy.

Figure 3. *Region chosen to demonstrate the Universities of Queensland approach to developing a range suitable for high speed testing.*

Figure 4/5. *Ground Control demonstration unit. Telemetry reception tests 32km from Ground Control.*

This is simply a demonstration and has all the hallmarks of a very low budget. However, it successfully demonstrated the concept. Reasonable funding could greatly increase this capability.

7. Management

The approach to management of the team is equally important as all of the above.

The team needs sufficient critical mass to sustain itself, but should not be more that 14 people. STAje- used on average 5 people and this was insufficient. HIFiRE used 14-22, but multiple flights were being worked concurrently. The most important aspect of the payload is that it is a system, which means, every part is interconnected. This means, every team member needs to be interconnected and well aware of the other members requirements and be in a position to change requirements when obstacles are encountered elsewhere. Typically, one aspect of the payload is more technologically advanced over another, so where these technologies combine to form a system, requirements on the least advanced technology can be relaxed by implementing the full capability of the advanced technology. The team members need to be aware where they can assist each other by implementing this approach to achieve the objective. This is achieved by weekly meetings where all must attend.

Risk adverseness is often cited as the death of a program. All responsible engineers are risk adverse. However, in the case of the technical lead, if they understand their area, they appear to be extremely risk-tolerant in the eyes of those that do not understand the technology, but in effect are generally conservative. Hence:

- **The Technical Lead** needs to be very competent and able to recognise and prioritise risks, and develop reasonable strategies to minimise them; and
- **The Program Manager** assists the Technical Lead.

8. Conclusion

- Australia has a unique niche in University-based hypersonic capability development. It has the knowledge, experience, and remote land areas necessary to execute highly cost-effective hypersonic flight trials safely, and at tempo.
- To achieve a high tempo of low-cost flights, the time to develop a payload must be reduced by embracing AM, COTS hardware and software, low energetic trajectories, bespoke rocket motors and developing a private range that is dedicated to high speed flight testing.
- This will significantly accelerate development and de-risking transition of technologies to the full-scale systems.
- STAje- builds on the lessons learnt from HIFiRE and is demonstrating this new approach.

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