Aerospace Reconnaissance Vehicle

Introduction

The design problem for the Spring 2000 semester is adapted from those used in Fall 1999, Fall 1998, and Fall 1997. It is for an unmanned space reconnaissance vehicle. The vehicle should use aeroassist to perform orbital transfers and large cross-range reentries. You are to determine whether the existing designs can be improved enough to make the design goals feasible. If you determine that the design goals are not feasible, then this should be demonstrated unambiguously. A successful preliminary or conceptual design is a prerequisite for a decision on proceeding to detailed design and manufacturing.

The design will be submitted in a final Design Disclosure Report, including an Executive Summary. Details of the requirements are on the following pages. Design teams will be formed during the first week of class.

The project is to be a team effort. One member of each team is to be selected as Project Leader by Tuesday 18 Jan. The Project Leader is responsible for overseeing and coordinating the design effort, in addition to his or her other responsibilities.

A schedule for progress reports will be handed out separately. The final Design Disclosure Report is due on Monday, 24 April 2000, at 12:00 noon, and the oral presentations of that report will be given on Wednesday and Thursday, 26-27 April. Four copies of this report are required, with three copies of the appendices. No late reports will be accepted.

Aerospace Reconnaissance Vehicle

This ARV vehicle is to be used to gather critical intelligence data at times of high international tension. The following paragraph from an NRO request for proposals indicates the general interest:

‘1.7 Reusable Launch Vehicles (RLV). The Office of Space Launch is interested in tracking the progress of the emerging RLVs and investigating their ability to help the NRO accomplish its mission. Identify operational, development, or reliability hurdles that must be overcome. Identify key development milestones. Provide recommendations for system architecture requirements (spacecraft dimension and orbit parameters best suited for each type of emerging RLV). Identify timeframes in which satellite and/or system parameters must be supplied in order to support the RLV design process. Provide recommendations for test and/or use of an RLV in a mixed Reusable Launch Vehicle/Expendable Launch Vehicle fleet. Investigate ways that emerging RLVs can impart evolutionary or revolutionary changes to accomplish the NRO mission.’ (National Reconnaissance Office, OSL BAA #99-0001, 31 March 1999, see also http://www.nro.odci.gov).

The present RFP addresses the possibility of a new class of vehicle with revolutionary reconnaissance performance, using high-efficiency aeroassist to perform low-cost changes in
orbit inclination, ascending node, and timing. The vehicle is to perform these missions by using the earth’s atmosphere to assist in 1) making orbital changes and returning to space, and 2) repeatedly viewing critical regions during an extended reentry with a large crossrange.

**Requirements for Sample Mission**

The vehicle must be capable of launching on short notice into a 100 nm (185.53 km) circular, retrograde orbit from the Barking Sands Missile Launch Facility on the island of Kauai, Hawaii. Launching into a retrograde orbit from this location makes the vehicle less vulnerable to early warning radars, and hence less likely to see hostile action. Survivability and effectiveness is enhanced by requiring that the vehicle be capable of changing orbit planes after the first pass over the specified site. The vehicle is unmanned, and must be capable of passing over either one of the following locations on the first orbit after launch: site (1) at 40.0 N and 132.0 E in North Korea, site (2) at 33.0 N and 40.0 E in Iraq. After passing over the given location, a decision will be made to either (a) deorbit and land at Kauai, (b) perform a maneuver to rotate the orbit plane to pass over the site on the next orbit, or (c) remain in orbit for an arbitrary time until additional intelligence is needed. Should the vehicle remain in orbit, its capability for performing further orbital transfers is to be shown. These would allow obtaining additional intelligence at intervals that the enemy cannot predict. The capability of the vehicle for making multiple overflights over the critical sites during reentry is also to be shown. Finally, the vehicle should be able to land at Kauai.

**Vehicle Requirements**

The vehicle must be launched on an existing expendable rocket. The vehicle mass will be used as a crude measure of cost, so it should be minimized. The vehicle mass is limited to the maximum that can be launched with an existing system.

The vehicle will be powered by throttleable, restartable rocket engines for altering the orbital plane, for deorbit, and for orbital insertion if needed. Only current rocket engines will be considered, to reduce development cost.

The reconnaissance equipment has a mass of 275 kg and occupies a volume of 1.5 cubic meters. A circular sensing port of 1.0 square meters will be provided; it must be capable of viewing the surface of the earth. Communications, antenna, electronics, and guidance equipment will require 300 kg and 0.5 cubic meters of volume. The vehicle requires 10 kW of power on a continuous basis, with a peak requirement of 45 kW during sensing and data transmission. A fully controlled lifting reentry will be made to return the vehicle to Kauai, for landing using a parafoil. A hatch of size 1.5 by 1.5 meters must open on top of the vehicle, near the center of gravity, for release of the drogue chute and parafoil, which have a mass of 140 kg and occupy a volume of 0.4 cubic meters. For the purposes of this study, the reentry trajectory may be terminated at an altitude of 10 km with a deviation of less than 0.5 deg. from the coordinates of the landing point at 22.0 N and 200.3 E.

Vehicle accelerations must not exceed 8.0 g’s. In addition to the primary rocket engines, the vehicle will be supplied with an orbital maneuvering system to control attitude, and be capable of supplying a 125 m/s velocity increment for positioning and possible docking with a satellite or the space station.

If this mission is attempted using only exoatmospheric propulsion, the vehicle weight and cost become prohibitive. This design effort is therefore initiated to determine if aeroassist
maneuvers can be used to achieve significant reductions in propellant requirements (Ref. 1). Such high-efficiency aeroassist maneuvers may be enabled by the recent development of ultra-high-temperature ceramics allowing the use of sharp noses on hypersonic vehicles. Repeated atmospheric maneuvers are allowed.

Because it uses aeroassist maneuvers that require entry into the earth’s atmosphere, the vehicle must have an aerodynamically efficient shape, be supplied with a thermal protection system (TPS), and accommodate the payload entirely within the vehicle. It is expected that the vehicle will be controlled aerodynamically during the aeroassist maneuvers to further conserve consumables. The TPS shall be reusable for 100 flights thus eliminating the use of ablators. Since maneuvers may be accomplished in the upper atmosphere, viscous interaction will occur and degrade the aerodynamic performance relative to inviscid values.

The TPS will be designed using the new Ultra High Temperature Ceramics recently flight tested by NASA and the Air Force (see http://kauai.arc.nasa.gov/projects/sharp/pl1.html). This new TPS material enables the revolutionary use of sharp leading edges on hypersonic vehicles (Ref. 2). This enables an increase in lift/drag ratio to about 4 or more. The primary motivation for this RFP is to determine whether this new material, and the design changes it permits, will enable a revolutionary improvement in performance.

Booster Requirements

An expendable booster shall be selected to launch the vehicle from the Barking Sands Missile Launch Facility into the 100 nm circular orbit, with the proper heading angle so that the orbiter passes over the desired location on first orbit. Due to the nature of the mission, launch must be carried out with a minimum of delay so that timely reconnaissance data can be obtained. Thus the boost phase must be carried out with solid rocket engines. Rocket engines may consist of an combination of existing engines or engine segments which will accomplish the mission, and boost acceleration should be limited to the 8 g maximum. Spent stages must be tracked to ensure they do not land in populous areas.

Revisions to RFP

The requirements specified in this RFP are a current best-estimate of the desired capabilities. The preliminary design work may show that some of the requirements make the design unfeasible, or grossly limit the design with insufficient cause. Proposers are encouraged to discuss the requirements with Prof. Schneider. They may be encouraged to submit a written Request for RFP Modification, giving justification for the requested change. If such a request is approved, it will be distributed to the other groups as an alternate version of the RFP.

Design Disclosure Report

This report shall be organized as follows. All data are to be reported in SI units.

Executive Summary – 10 pages maximum (separately bound)

A brief clear description of what the system is, what it can do, and how it meets requirements. It should include key performance results and design trades. Use figures, plots, etc.,
in conjunction with the text to effectively communicate your results. Include at least one three-view drawing of your vehicle design, with the overall dimensions, the initial and dry masses, and the synergetic efficiency. Write the Executive Summary assuming it may be the only thing an important customer/evaluator may read. A Executive Summary of sufficient quality may be sent to NRO for review.

Introduction to the Design – 10 pages maximum
This section should give an introduction to the design problem as a whole, and to your vehicle.

Comparison to Previous Designs – 10 pages maximum
This RFP is similar to those issued in the Fall of 1997, 1998, and 1999, so several design reports are available. Compare the performance of your design to that of the previous designs, and discuss the reasons for the changes in vehicle design and performance. If you based your analysis code on one of their codes, identify any errors you may have discovered.

Boost Vehicle Design and Vehicle Propulsion – 30 pages maximum
Describe the booster design indicating stage thrust and Isp values, and show that the vehicle is capable of being launched into each of the two required orbits. Present a drawing of the combined ascent vehicle, a complete mass statement, and show that the vehicle is controllable during ascent (i.e. that each booster stage has thrust vector control sufficient to accommodate the upper stages and maintain control including 95 percentile worst month winds). Present plots of critical boost trajectory parameters, such as time variations in velocity, thrust, mass, altitude, flight path angle, acceleration, and stagnation point temperature. Show the impact locations of all booster stages, and make sure booster impact is not near populated areas.

Describe the propulsion system and propellant requirements (mass and volume). Use an existing flight-proven propulsion system rather than designing your own. Show propellant use schedule for each maneuver (e.g. boost, circularization, aeroassist phases, deorbit retrofire, etc.) If the system is used within the atmosphere during the aeroassist maneuvers, account for the effects of the atmosphere on performance. Describe the design of the ARV propellant tanks, and indicate size, mass, and location for the orbiter engines and the attitude control thrusters. Describe the attitude control and orbital maneuvering system and show propellant requirements, including the 125 m/s ΔV required for maneuvering.

Trajectory/Performance Analysis – 30 pages maximum
Discuss the orbit parameters for each of the two locations, and indicate the times that are available for reconnaissance. Select several missions for detailed analysis, and give the justification for the selection. Describe the aeroassist maneuvers used to achieve the orbital changes. Compare the synergetic performance to the performance of exoatmospheric pure-propulsion trajectories. Discuss the tradeoffs involved in selection of the synergetic trajectory. Develop a time line for the mission, and show ΔV requirements for each portion. Provide a graphical summary of these maneuvers including normal and lateral load factor histories, aeroheating, synergetic efficiency, and so on. Discuss the proportion of overall
energy losses used up in the rarefied-flow viscous-interaction aerodynamic regime. The trajectory calculations should show that the vehicle can arrive within 0.5 deg. of latitude and longitude above the target viewing area.

Reentry Trajectory (5-person groups) – 30 pages maximum

Describe the maneuvers to be used in reentry, including the capability for reconnaissance during reentry, perhaps using skipping maneuvers. Show the crossrange obtainable and the footprint envelope the vehicle can achieve over the United States. Analyze the ground track for repeatability, and show what conditions are necessary for the vehicle to land. The trajectory calculations should show that the vehicle can arrive within 0.5 degrees of latitude and longitude from the landing site coordinates at 10 km altitude, after which the parafoil is used to execute a landing. Present detailed information about typical reentry trajectories, such as the time variations of velocity, altitude, flight path angle, latitude, longitude, heading angle, acceleration, and surface temperatures at several locations on the vehicle.

Aerothermodynamics – 30 pages maximum

Develop an aerodynamic model for the vehicle in hypersonic and supersonic flow, and determine lift, drag, and moment coefficients. For appropriate center of gravity locations, examine trim and stability in pitch and yaw. Correlate L/D ratio with crossrange capability. Develop empirical lift and drag coefficients for supersonic flow and provide a smooth transition from hypersonic to supersonic flight conditions. Determine if a significant portion of the overall vehicle energy is lost in the rarefied-flow viscous-interaction regime, and if so implement improved models for this regime.

Provide aerodynamic heating environments for all missions. In cooperation with structures, select TPS material and specify thickness requirements to keep substructure temperatures within required limits. Show temperature histories for critical structural components.

Structures and Loads – 30 pages maximum

Describe the structural design of the vehicle and materials used. Show how all parts fit within the available space. Show the structural margins for major components. Provide a complete mass statement including the masses and center of gravity of all components including expendables and personnel. Provide three-view drawings, inboard profile, and plan view drawings showing the location of major components.

Appendices – No page limit and separately bound

Do not put any essential material in the Appendices. They should be viewed as backup data which an evaluator can consult for additional detail if desired. Extended tables should be provided electronically, in ASCII. Codes should be provided in electronic form. Code documentation in the form of comments and references should be sufficient to allow the reader to use and modify the code.

General Notes

The reports shall be presented on one side of the page only. Any section with more than the above specified number of pages will be judged on the contents up to the allowable number of pages. A table of contents with page numbers will be provided. A compliance
matrix will also be provided: this is a cross reference of all the requirements, with the page number in the report where the requirement is shown to be satisfied.

Graphs and figures do not have to be a full page. In fact, several smaller figures are often more useful than one large figure. All figures should be referred to in the text by number so that the relationship of the figures and text is clear. The data plotted in the figures should be provided numerically in the appendices.

In all sections, describe the reasons for major design decisions. Is the design a ‘best’ or excellent one? In what ways, and why do you think so? What were the limitations on your ability to come up with the ‘best’ design? What are the most important limitations in your analyses? What are the next steps you would take if authorized (or funded) to proceed further with the design?

References to other documents or other sections of your report should contain page numbers as well as document citations or section numbers.

**Evaluation of the Designs**

Grades will be determined by Prof. Schneider based on the individual’s work, and their ability to communicate and interact in a timely manner with the other members of their team. The following factors are also of importance:

- Innovation
- Understanding of all aspects of the problem
- Technical validity
- Design completeness
- System integration
- Ability to meet requirements
- Neatness and professional presentation (without embellishments)

**References**
