STAFF SUMMARY SHEET

	TO	ACTION	SIGNATURE *(Surname)*, GRADE AND DATE		TO	ACTION	SIGNATURE *(Surname)*, GRADE AND DATE
1	DFM	coord	LtCol 22 Feb (Department Head or Designee)	6			
2	DFER	approve	Brent A Rutherford Col 24 Feb 2012	7			
3	DFAS	info	(Author /Originator)	8			
4				9			
5				10			

SURNAME OF ACTION OFFICER AND GRADE	SYMBOL	PHONE	TYPIST'S INITIALS	SUSPENSE DATE
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SUBJECT
Clearance for Material for Public Release USAFA-DF-PA -60

DATE
20120216

SUMMARY

1. PURPOSE. To provide security and policy review on the document at Tab 1 prior to release to the public.

2. BACKGROUND.
Authors: C1Cs Kyle MacDonald, Gabe Paterson, Eric Wilson, Tom Kashul, and Frank Genco
Faculty advisors: LtCol Tom Joslyn (DFAS) and LtCol Troy Harting (DFM)
Title: Liquid Stream Propulsion Technology

Circle one: Abstract Tech Report Journal Article Speech [✓ Paper] Presentation Poster Thesis/Dissertation Book Other: ____________

Description: This project summary will be entered into the 2011 National Security /Innovation Competition sponsored by the Colorado Homeland Defense Alliance.

Release Information: NSIC Conference at UCCS (27 Apr, 2012).

Previous Clearance information: a previous iteration of this concept was approved for NSIC 2011 in February 2011 under USAFA-DF-PA-067, routed by Dr Kurt Heppard (DFM)

Recommended Distribution Statement:
(Distribution A, Approved for public release, distribution unlimited.)

3. DISCUSSION. This summary paper describes a current capstone project.

4. VIEWS OF OTHERS. none

5. RECOMMENDATION. Department Head or designee reviews as subject matter expert. DFER reviews for policy and security. Coordination indicates the document is suitable for public release. Suitability is based on the document being unclassified, not jeopardizing DoD interests, and accurately portraying official policy [Reference DoDD 5230.09]. Release is the decision of the originator (author). Compliance with AFI 35-102 is mandatory.

Troy Harting, LtCol, DFM
Assistant Professor

1 Tab
1. Summary paper

Liquid Droplet Stream Propulsion System

TEAM MEMBERS: Frank Genco, Tom Kashul, Kyle MacDonald, Gabriel Paterson, and Eric Wilson[1]

ADVISORS: LtCol (Dr) Thomas Joslyn, LtCol (Dr) Troy Harting, US Air Force Academy

Introduction

Liquid stream propulsion technology is a unique satellite propulsion innovation that uses the constant transfer of momentum through projection of silicon oil droplet streams through space. Fluid streams are generated on each spacecraft, projected to their companion spacecraft which collects the stream and continuously sends fluid back to the first spacecraft. The system allows paired satellites to fly side-by-side in formation and maintain a constant distance between them in order to conduct special missions such as interferometric synthetic aperture radar (InSAR) observations. Benefits of InSAR to National Security include high-resolution topography to increase awareness of IEDs, underground activity detection, and damage assessment, even at night and under cloudy conditions. The liquid stream propulsion technology offers tremendous advantages in terms of increased energy efficiency, reduced weight, advanced maneuverability, overall cost reduction, and possible use as a means to remove orbital debris. Droplet streams of diameters and speeds demonstrated in research to date satisfy propulsion needs of 1000 kg or smaller satellites in any earth orbit with at least a kilometer of separation. Compared to electric propulsion, a droplet stream system produces equivalent thrust but requires less than 1% of the power and only 20% of the mass of a traditional system to do so.[2] The weight and power savings will greatly reduce the cost to operate and launch satellites carrying the liquid stream propulsion technology.

Technical Analysis

Concept

Engineers have established the feasibility of using droplet streams projected over a short distance to remove heat from large structures in space as a substitute for radiators. The concept is known as a Liquid Droplet Radiator (LDR) and it has seen successful component development and drop tower microgravity testing. An LDR provides large space structures with more flexible and more mass-efficient thermal control than conventional radiators. Active thermal control is possible by adjusting the flow of fluid to increase or reduce heat transfer to or from desired spacecraft

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[1] Aided by previous research from Steve Vrabic, Frankie Lugo, John Red, Anthony Alt, Jeremy Warfield, Cody Gentry, Captain Angie Fedden, and Dr. Thomas B. Joslyn.

[2] Joslyn, T. Charging Effects on Fluid Stream Droplets for Momentum Exchange Between Spacecraft. PhD Dissertation, Department of Mechanical and Aerospace Engineering, University of Colorado, Colorado Springs, Nov, 2009.

components.[3] The same droplet streams that provide cooling when aimed toward an on-board collector are also useful for exchanging momentum between spacecraft that pass close enough for stream transfer, thus offering the potential to use this technology for propulsion.

Recent work at the University of Colorado demonstrated droplet production using solenoid valves shown in Figure 1.[2] These valves can operate for several million cycles and are capable of generating a droplet stream for 3-5 years. To overcome the short life of the valves many redundant valves can be flown on each spacecraft due to their low cost and size. Two types of micro-solenoid valves were tested in the Colorado study and were found to produce droplet streams of sufficient uniformity, size, and speed to satisfy propulsion requirements for 1000 kg satellites spaced more than 1km apart. When compared to piezoelectric droplet generators developed for the LDR program, solenoid generators also produce less vibration and can produce any desired gap distance between droplets. This is useful because gaps between droplets reduce the impact of electrostatic forces acting between charged droplets that can cause dispersion of transiting charged droplets from the intended path.[2]

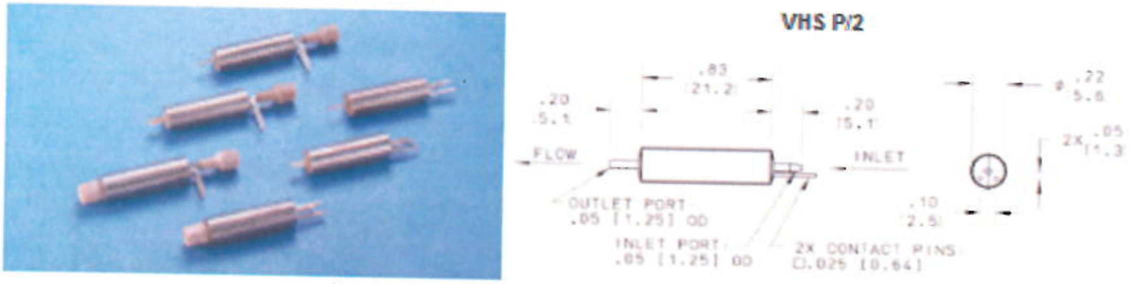

Figure 1. Lee Company Solenoid Micro Valve Specifications.

LDR research resulted in at least two collector designs, shown in Figure 2, that are viable for use in a droplet stream propulsion system. One collector is a rotating cylindrical drum that gathers fluid via a pitot tube. The other design is called a linear collector and relies on the momentum of incoming droplets to drive fluid to the gear pump intake for pressurization.[2]

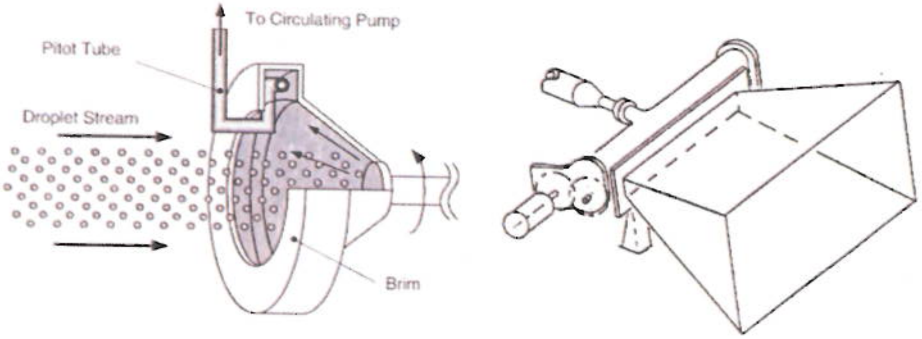

Figure 2. Rotating collector (from Totani, et al., 2006) and linear collector (from Pfeiffer, 1989).

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[3] Totani, T. Kodama, T., Nagata, H., Kudo, I., Thermal Design of Liquid Droplet Radiator for Space Solar-Power System. Journal of Spacecraft and Rockets, Vol. 42, No. 3, May-June 2005.

Benefits of Liquid Stream Propulsion Technology

Research has demonstrated the utility of using droplet streams to produce the thrust needed to maintain constant separation of two spacecraft travelling side-by-side. Tandem side-by-side flight allows for InSAR observations that provide resolutions of less than 5 cm.[4] This is nearly an order of magnitude better than typical synthetic aperture radar, which is over a meter. Additionally, fluid streams transiting between spacecraft also allow for maneuvering to foil attempts by adversaries to track or intercept them. Moreover, the ability to accurately project a stream of fluid over distances in excess of 50 km allows the deflection or de-orbiting of debris which may threaten this spacecraft or other national assets in Low Earth Orbit.[5]

The benefits of InSAR offer the 21st century warfighter a large increase to field information that is immediately useable. InSAR works by taking two extremely high resolution images and comparing them to detect changes in the images. This currently allows geologists to track swelling in the earth's crust by as few as 5 cm. We can apply this technology to the battle field by searching for camouflaged weapon stashes and roadside bombs. High resolution images show changes from when the last image was taken. Soldiers on the ground can notice disruptions on the ground, for example, in the case of a bomb placed over night. InSAR can also offer soldiers the ability to look for new structures that normally would have been overlooked in an intelligence report. Even if an object is covered with some sort of concealment, this new technology will be able to help point it out.

Industry Analysis

Due to its applicability for national security spacecraft, the projected initial target market for the Liquid Stream Propulsion Technology is the DoD. According to the fiscal year 2012 defense budget, $10.2 billion is included for the DoD Space Program to maintain U.S. supremacy in space. An additional, $12.2 billion is included for science and technology funding – a 25% increase since 2000.[6] The market for satellite propulsion systems is dominated by a limited number of suppliers in both the liquid and solid propellant markets. The liquid propellant market generates $1 billion annually. Pratt-Whitney Rocketdyne supplies 68% of the market and Aerojet supplies 17% of the market.[7] Both of these suppliers provide liquid satellite propellant systems for the DoD space programs.

The costs associated with keeping two satellites in tandem for InSAR are what make the droplet stream system an enabling technology. In order to keep two satellites (weighing 500 kg in LEO

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4 "InSAR Workshop Summary Report." Solid Earth. NASA, 22 Oct. 2004. Web. 2 Feb. 2012.

5 Tan, Xian Yang Calvin, C. Fluid Required To Lower Derelict Sat, Department of Mechanical and Aerospace Engineering, University of Colorado, Colorado Springs, Feb, 2012.

6 Office of the Under Secretary of Defense. United States Department of Defense Fiscal Year 2012 Budget Request. Publication. Feb. 2011. Web. 16 Feb. 2012.

7 Space Propulsion Systems Inc. Space Propulsion Systems: Enabling the Commercialization of Space. Rep. Space Propulsion Systems Inc., 2006. Web. 16 Feb. 2012.

at 300 km with a transit speed of 50 m/s) 1km apart from each other in space, each satellite would need 6 RIT-22 Ion Thrusters. These 6 ion thrusters would require a combined 30 kw of power. To put this in perspective, there are 8 solar panels providing power to the International Space Station (ISS). One solar array wing weighs over 2,400 lbs and is capable of generating 31 kW of power.[8] In order to power a satellite with 6 RIT-22 Ion Thrusters you would need an entire solar array wing off of the ISS. Assuming the industry average launch cost of $13,000/kg it would cost over $14 million to launch one satellite kept in tandem with ion thrusters. In comparison, the droplet stream system uses .167% or nearly 1/600th of the power that 6 ion thrusters would require. The cost to power the droplet system is negligible when compared to costs associated with ion thrusters, which makes tandem satellites financially feasible.

	Droplet Stream	6 RIT-22 Ion Thrusters
Power Consumption (W)	50	30000
Launch Weight (kg)	34	1137
Launch Costs ($k)	442	14781

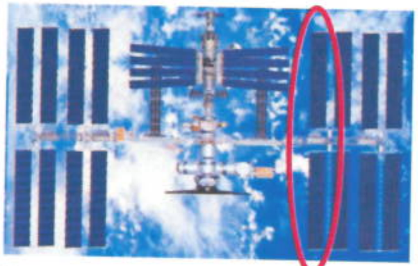

Figure 3. Launch Cost Comparison of Tandem Propulsion Systems and Solar Array Panels from the ISS.

Market Analysis

According to the ASPRs Ten-Year Remote Sensing Industry Forecast the demand for the highest levels of resolution have not been met; data users want higher resolution content. The most significant issues that continue to represent large challenges and opportunities within the remote sensing industry are: the demand vs. cost in an uncertain economy for high spatial resolution and new sensor data, both aerial and satellite, meeting the increase in demand for higher levels of education in geographic information system (GIS) and newer imaging technologies, and the conflicting roles of national governments in developing remote sensing platforms and products while limiting access and use of data.[9] More specifically, spatial resolution, geo-locational accuracy, and vertical accuracy are lacking in terms of the quality of data needed versus quality of data currently being used. Refined InSAR capability, enabled by tandem satellites using droplet propulsion to maintain the desired separation, provides a means to realize the greater imaging quality required by today's users.

Currently, only one pair of satellites in the industry provides an InSAR capability, TanDEM-X and TerraSAR-X, a pair of German radar satellites orbiting the Earth in a unique satellite formation. However, they are limited by baseline separation; the satellites are not always side-by-side tandem and thus cannot always perform InSAR optimally. The revisit time for the German Satellites is 2.5 days which may be quite long when trying to use InSAR for

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[8] "STS-97 Payload: PHOTOVOLTAIC ARRAY ASSEMBLY (PVAA)." Shuttle Press Kit. NASA, 11 Sept. 2000. Web. 16 Feb. 2012.

[9] Modello, Charles. "ASPRS TEN-YEAR Remote Sensing Industry Forecast." Web. 13 Feb. 2011.

applications. LDR technology provides our system with a radiation system for cooling and also allows our spacecraft to maneuver efficiently in space; the two current tandem satellites do not have these attributes, therefore creating an opportunity in the market.

Remote sensing is also becoming of greater importance on the international stage. In the recent report *Military and Security Developments Involving the People's Republic of China*, China alone launched nine new remote sensing satellites in 2010 which can perform both civil and military operations. "China is deploying imagery, reconnaissance, and Earth resource systems with military utility. Examples include the Yaogan satellites, the Haiyang-1B, and the Huanjing disaster/environmental monitoring satellite constellation. China is planning eight satellites in the Huanjing program that are capable of visible, infrared, multi-spectral, and synthetic aperture radar imaging. China currently accesses high-resolution, commercial electro-optical and synthetic aperture radar imagery from all of the major providers including Spot Image (Europe), Infoterra (Europe), MDA (Canada), Antrix (India), GeoEye (United States), and Digital Globe (United States)."[10]

Recommendations

Using the technical report *Guidelines and Metrics for Assessing Space System Cost Estimates* by the RAND Corporation in 2008, the development costs for a propulsion system on a surveillance mission would range between 2 to 4 million dollars.[11] This has not been confirmed by an independent technical analysis, but because development started almost 30 years ago these costs would be significantly lower. Droplet Stream propulsion enables **continuous** InSAR at a feasible cost. The benefits of continuous InSAR will change the dynamic of information in war-fighting by providing superior radar imaging to U.S. military forces. With hyper accurate renderings of the area and the ability to compare two images taken over periods of time to check for potential threats that have been placed overnight with an unparalleled degree of accuracy, the 21st century war-fighter will be able to lead a safer and more efficient battle. For these reasons, we believe this technology is a necessity to National Defense. It is recommended that further testing of the Droplet Stream Propulsion System take place in space – a feat yet to be attempted. Since successful collector, pump, and generator designs have been tested within the last 5 years in the US and Japan it is expected that a working Droplet Stream Propulsion System can be developed and tested in less than 15 months.

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[10] Office of the Secretary of Defense. *Military and Security Developments Involving the People's Republic of China*. Rep. Department of Defense, 2011. Print.

[11] Fox, Bernard, Kevin Brancato, and Brien Alkire. *Guidelines and Metrics for Assessing Space System Cost Estimates*. Tech. Santa Monica, CA: RAND Corporation, 2008. Print.