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Exploring the depths of Kraken Mare – Power, thermal analysis, and ballast control for the Saturn Titan submarine

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ABSTRACT

To explore the depths of the hydrocarbon rich seas on the Saturn moon Titan, a conceptual design of an unmanned submarine concept was recently developed for a Phase I NASA Innovative Advanced Concept (NIAC) study. Data from Cassini Huygens indicates that the Titan polar environment sustains stable seas of variable concentrations of ethane, methane, and nitrogen, with a surface temperature around 93 K. To meet science exploration objectives, the submarine must operate autonomously, study atmosphere/sea exchange, interact with the seabed at pressures up to 10 atm, traverse large distances with limited energy, hover at the surface and at any depth within the sea, and be capable of tolerating multiple different concentration levels of hydrocarbons. Therefore Titan presents many cryogenic design challenges. This paper presents the trade studies with emphasis on the preliminary design of the power, thermal, and ballast control subsystems for the Saturn Titan submarine.

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1. Introduction

The purpose of this paper is to present the results of a NASA Innovative Advanced Concept (NIAC) Phase I study for a conceptual design of an unmanned submarine to explore the extraterrestrial seas of Saturn Titan. The goal of NIAC is to "enable exciting, unexplored, credible aerospace concepts with at least one mission application that addresses NASA goals". The concept developed was for a direct, one year mission to Titan. The submarine is a unique, unprecedented submersible design that operates within the liquid hydrocarbon seas of Titan and is fully autonomous to carry out detailed scientific investigations of the sediments, seas, and shores. Specifically, the submarine trade studies are presented for the power, thermal control, and ballast control subsystems.

The outline of the paper is as follows: First the background section presents motivation for researching Titan and unique features of the Titan environment related to design of the submarine. Then an overview of the Titan submarine mission is given, including science requirements, high level system design requirements, and a high level mission concept of operation. Next, an overview of the submarine concept is presented, along with vehicle design and preliminary subsystem trades. Then the trade studies and ensuing analyses and designs are presented for the power, thermal, and ballast subsystems.

2. Mission

NASA and the space flight community maintain a strong desire to develop technology to enable robotic and manned space missions beyond Low Earth Orbit (LEO). One such destination that has both captivated and puzzled humanity is Saturn and its moons. Data from both Voyager and Cassini Huygens have uncovered a plethora of information pertaining to the evolution of the Saturn system. Both missions have proven to be highly prestigious in shaping our understanding of the solar system. The original purpose of the Voyager I mission was to conduct fly-bys of Jupiter, Saturn, and Titan. Voyager I has since travelled beyond Pluto. The original purpose of Cassini was to analyze Saturn and probe the surface of the moon Titan [1–9]. It has since provided surface and atmospheric data of numerous other bodies within the Saturn system.

The primary motivation behind many planetary missions has been the search for intelligent life (at least as humankind can perceive), and so places nearest the Earth, such as the Moon and Mars have garnered the most amount of attention. Although

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Nomenclature

A	area (m^2)
c_p	specific heat (J/kg K)
d	characteristic length (m)
g_T	gravity on Titan (m/s^2)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	characteristic length (m)
m	mass of a molecule (kg)
n	number
Nu	Nusselt number
P	pressure (Pa)
Pr	Prandtl number
Q	heat (W)
Ra	Rayleigh number
Re	Reynolds number
T	temperature (K)
t	thickness (m)
V	velocity (m/s)
x	mole fraction
Y	mass fraction
z	depth (m)

Greek

μ	Viscosity (Pa s)
ρ	density (kg/m^3)

Subscripts

c	convective
cl	coolant loop
f	film
i	insulation
lm	liquid methane
mix	mixture
s	surface
ss	structural supports
vp	view port
w	wire
T	Titan

there is evidence that suggests that life is possible beyond Mars, the question thus arises, why explore Titan? Three primary reasons are cited:

1. To determine if hydrocarbon based life is possible on Titan.
2. To improve our understanding of the history and evolution of hydrocarbons in the solar system.
3. To provide a pathfinder for later designs of submersibles in the seas hidden beneath the ice crust of other outer planet moons.

Table 1 lists features of Titan, Earth Moon, and the three most likely icy moons where life (as humans know it) is possible, Europa, Ganymede, and Enceladus. Shown in Table 1 are the home planet of the moon, the relative size among all the moons in the Milky Way, the radius, the mass of the moon divided by the mass of Earth, and the average temperatures at the equator and poles.

2.1. Saturn Titan cryogenic environment

As shown in Table 1, Titan is the second largest planetary satellite in the Milky Way. Titan offers a unique exploration opportunity due to the dense atmosphere, low gravity (14% of Earth gravity), and stable hydrocarbon seas as mapped by Cassini. Titan is of great interest to astrobiologists and geologists. Titan's unique features that impact design of the cryogenic submarine, in terms of assumptions made and inputs to models and trade studies, are as follows:

1. Titan is the only known body (other than Earth) within the solar system with stable seas; data from Cassini show that stable hydrocarbon lakes exist at the Titan poles.

Fig. 1 shows a Cassini image of Titan's north polar regions on October 7, 2013, acquired at some 1.3 million kilometers from Titan. At upper left, near the north pole, are several dark patches – these are Titan's seas. Fig. 2 shows a compilation of flyby images from Cassini. The seas are similar in size and depth to the Great

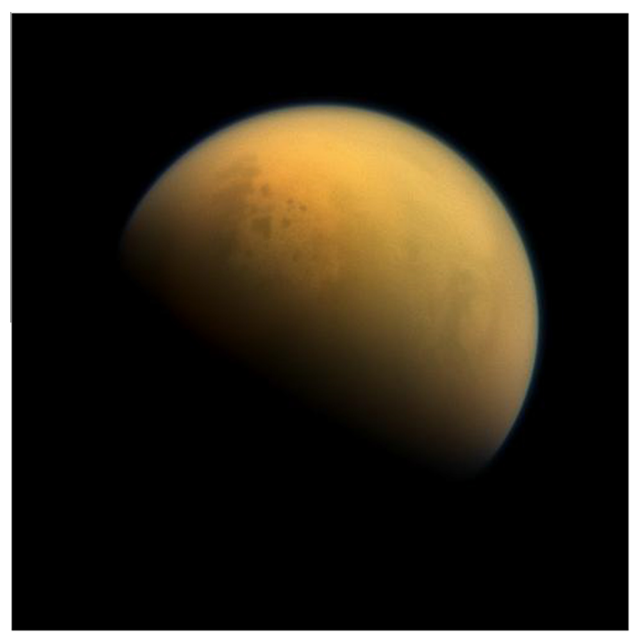

Fig. 1. Cassini image of the north polar region on Titan.

Table 1
Comparison of earth moon and Titan with other icy moons.

	Moon	Home	Relative Size	Radius (km)	Mass/earth Mass (%)	Avg. T Equator (K)	Avg. T Poles (K)	Notes
1	Europa	Jupiter	6th	3100	0.803	110	50	200 m thick ice
2	Ganymede	Jupiter	1st	5268	2.47	155	116	800 km thick silicate rock + ice
3	Enceladus	Saturn	~17th	513	0.0018	80	85	30–40 km ice shelves
4	Moon	Earth	5th	3472	1.23	260	33	
5	Titan	Saturn	2nd	5150	2.25	97	94	Ice/rocks/dunes; Stable hydrocarbon lakes @ poles