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PROJECT TIN TIN - INTERSTELLAR NANO MISSION TO ALPHA CENTAURI

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Currently there are no interstellar exploration missions planned or in progress. Even the Voyager spacecraft will not pass close to a neighbouring solar system for tens of thousands of years. The pursuit of deep space and interstellar exploration studies has recently become a matter of critical debate, with Icarus Interstellar and the 100 Year Star Ship (100 YSS) program drawing attention to the merits of pressing the boundaries of current and near future technologies towards such goals. Project Tin Tin is a mission profile and spacecraft design feasibility program which aims to establish the science, propulsion, communications, power and materials which will be used to build interstellar precursor missions using cubesats. The mission objectives are (a) to establish a program of utilizing space systems miniaturization technologies, (b) to create a template mission and spacecraft package for space-proofing interstellar systems and (c) to launch the first ever interstellar spacecraft to Alpha Centauri. In this paper and presentation we establish that an interstellar journey to our nearest star is feasible within 25,000 years using current technology, cutting Voyager's best time to a nearest star by a factor of 1/3, with reasonable room for improvements.

I. SCOPE OF PROJECT TIN TIN

There is currently renewed excitement in field of interstellar research and exploration. In January 2012, NASA/DARPA awarded a grant for the formation of a 100 Year Starship (100YSS) organization, which would foster the organizational sustainability required to pursue a century-long interstellar program [1]. In September 2012 DARPA also awarded a grant to the Global Alliance of Makers Building Interstellar Technologies (GAMBIT), with the objective of connecting "hackerspaces" to enhance humanity's survival on Earth and in space [2]. Icarus Interstellar, a volunteer research organization founded in 2009, is dedicated to achieving interstellar flight by the year 2100 [3] and was a partner in the successful 100YSS award.

Fundamental to a scientifically meaningful and technically redeeming interstellar exploration program however, is a series of incremental interstellar pathfinder missions. History shows how such roadmaps can easily become derailed by the lack of nationally sponsored funding, policies and the requirements to validate advanced technologies by progressing them through Technology Readiness Levels (TRL), which often require many years of modelling and laboratory prototyping.

Proposals such as the NASA/NIAC Realistic/ Innovative Interstellar Explorer [4] and several other technically feasible mission concepts proposed in the last decade, offer tangible scientific benefits using heritage technologies. In 2015, after its brief but meaningful encounter with Pluto, New Horizons will join the short list of interstellar probes alongside the Pioneer and Voyager spacecraft. There are no additional interstellar missions planned, and even Voyager-2, the fastest moving spacecraft, will not pass close to a neighbouring solar system for hundreds of thousands of years.

Cubesats have been used in a wide number of reduced scope missions in Low Earth Orbit (LEO) utilizing miniaturized space technologies and affordable, commercial off the shelf (COTS) equipment. Offering an attractive mass budget, efforts are underway to design lunar, asteroid and planetary exploration missions [5], using currently available launcher and propulsion technologies.

Project Tin Tin is an effort to lay the foundations for cost-effective technology and engineering validation Cubesat missions, leading up to the first interstellar precursor mission to Alpha Centauri. The objective of Project Tin Tin is to motivate interstellar exploration by pushing the envelope of what is currently possible for deep space exploration.

The Project Tin Tin research team aims to design, model and pursue the launch of a set of nanosat-sized spacecraft, or "Tins", with technical and scientifically relevant objectives starting in 2015. The mission objectives include:

(a) Assessing current capabilities for near future interstellar precursor nanosat missions,

(b) The incremental space validation of enabling technologies in propulsion, power, communications, structures, fabrication, telemetry and sensors and

(c) To launch the first interstellar spacecraft on route to Alpha Centauri, by the end of the decade, beating Voyager's ascribed 75,000 year time to arrival.

II. TO ALPHA CENTAURI BY CUBESAT

Project Daedalus (1973-1978) [6] was the first starship design study to demonstrate that interstellar flight was possible. The 50,000 tonne design called or a sustained pulsed inertial confinement fusion propulsion engine fuelled by Helium-3 mined from the Jovian atmosphere and required ~TW/kg power sources to achieve a fly-by of Barnard's Star, 6.8 lyrs away, with a speed approaching 12.6% c in only 46 years.

Project Icarus, *Son of Daedalus* is a unique, crowdresearched interstellar probe design and engineering challenge, which remains in hot pursuit of its sizable objectives by projecting the current state-of-the-art (SOTA) in space systems, out to the end of the century.

Project Tin Tin, however will use current technologies, ingenuity and imagination to demonstrate existing capability to explore interstellar space, while paving a path towards exploring Oort cloud objects, the Sun-gravitational focus and in-situ investigations of some of the extra-solar planets being observed, amongst others [7].

We present an *idealized* calculation demonstrating that essential capability for an interstellar nanosat mission exists today, using technologies rooted firmly on the upper echelons of the TRL scale.

The objective of our first interstellar precursor mission is to arrive at Alpha Centauri, 4.24 lyrs away, in ~25,000 years, improving on Voyager's iconic 75,000 yr trip time by a factor of ~1/3. We will use current systems and our Tin will weigh a total of 10 kg, remaining within the formal range of a 3-9 U Cubesat.

We assume the spacecraft is initially moving in a hyperbolic orbit with negligible initial velocity, such as the total needed velocity increment at burnout is 50.85 km/s, ignored gravity drag for this demonstration. Alpha Centauri however, has a radial velocity of 25.1 km/s [8], therefore our relative final velocity v_f becomes 25.74 km/s. We allocate half of the mass of our spacecraft to propellant, therefore the mass ratio R, defined as the initial over the final mass is 2. The Tsiolkovsky equation then gives us the necessary exhaust velocity for this mission profile:

$$v_{ex} = \frac{v_f}{\ln R} = 37.14 \ km/s$$
 (1)

The corresponding Isp is given by:

$$I_{sp} = \frac{v_{ex}}{g} = 3,786 \quad s$$
 (2)

a reasonable value given the wide selection of station keeping Field-Emission Electric Propulsion (FEEP) thrusters with Isp~3,000 s available today (Section III).



Fig. I: A concept rendering of an interstellar Tin, equipped with ion thrusters and supplemented by solar sails.

Having identified our idealized Isp in the range of current FEEP thrusters, we choose a long time to burnout t_b of 20 years, as representative of ion engine performance. The mass flow of our engine is thus:

$$\dot{m} = \frac{m_p}{t_b} = 7.9 * 10^{-9} \quad kg \,/\,s \tag{3}$$

We can now calculate the real performance of our engine by calculating jet power:

$$P_{jet} = \frac{1}{2} \dot{m} v_{ex}^{2} = 5.46 \quad W \tag{4}$$

If we assume our interstellar grade engine has an above average jet efficiency of η =0.7, the total propulsion system power utilization is:

$$P_{prop} = \frac{P_{jet}}{\eta} = 7.81 \quad W \tag{5}$$

Critical to the performance of all ion engines is the electrical power output per unit mass (W/kg) that the spacecraft power source is capable of supplying to the engine. As our interstellar precursor will operate at great distances from the sun, we select a nuclear battery as the power source. This decision lets us avoid complicated solar panel area, and power vs. distance from Sun calculations to simplify this exercise. We use the power source performance characteristics of the recently developed Advanced Stirling Radioisotope Generators (ASRG) [9], which is said to reach α ~10 W/kg at maturity. Therefore, to power our propulsion system the miniature ASRG would have mass:

$$m_{RTG} = \frac{P_{prop}}{\alpha} = 0.78 \quad kg \tag{6}$$

The final mass budget is shown in Table I.

Total Mass (kg) ~ 9 U Cubesat	10.0 (kg)
Propellant	5.00
ASRG Power	0.78
Total Engine Assembly	1.00
Instruments and Payload	1.00
Spacecraft Structure	1.00
Remaining Mass (kg)	1.22

Table I: Idealized Tin Tin mass budget, indicating a 25,000 year mission to Alpha Centauri is realizable.



Fig. II. Simplified Tin Tin Cubesat trip time to Alpha Centauri plotted against Isp and power supply specific power α (R=2, m=1.22 kg surplus). The graph suggests a clear pairing between power source capability and the propulsive characteristics of the Cubesat thrusters.

We have allowed a mass surplus of ~ 1.22 kg to account for the added mass for a telecommunications system and the instrument power regulation requirements. We have also ignored the velocity increment lost to gravity drag as the spacecraft leaves the solar system, which can be partially recovered through gravitational assist manoeuvres. Radiator mass has also been ignored, which becomes significant when nuclear power sources are used. A full systems integration study will be presented in a subsequent paper.

It is worth noting an important trade-off made evident in the above analysis. The Isp being of the order 3500-4500 s is clearly within the reach of current technology, while significantly higher specific impulses have been reported of the order of 10,000-30,000 s in some laboratory case studies supported by engineering data [10] [11]. At Isp ~15,000 s the trip to Alpha Centauri can be halved to 12,500 years compared to our case study above. With these figures the engine's jet power which tends to ~50 W, the specific power of the power source would have to increase by a factor of 7 to α ~50 W/kg (Figure II).

The objective of this exercise was to demonstrate that a fertile trade space exists for designing interstellar

Cubesats. The mission of Project Tin Tin, namely to launch the first human - made object to another star is therefore, realizable within the current decade.

In the following sections we present a selection of currently available technologies, which are conducive to Project Tin Tin objectives.

III. ASSESSMENT OF ENABLING TECHNOLOGIES

We have identified several enabling technologies vital for the development of interstellar nano-missions and as candidates for technology demonstration.

The objective of the various "Tin" missions can be characterized as path-finding missions for rapidly space validating state-of-the-art technologies. We focus on those of primary importance to deep space and interstellar exploration, relevant to Cubesat/ Nano are (a) propulsion, (b) power and (c) communications.

The scientific objectives of deep space and interstellar missions have been outlined in other key references [12].

III.I Propulsion and Launch Opportunities

FOTEC Indium Ultra-FEEP Thruster

The Ultra-FEEP thruster, under development by FOTEC in Austria, is a compact sized thruster capable of very high specific impulses (Isp) ranging from 20,000-100,000 s depending on the applied emitter voltage.

The core of the Indium FEEP thruster consists of a Liquid Metal Ion Source (LMIS) which has been used for active spacecraft potential control in several scientific missions, cumulating more than 15,000 hours of space operation [13]. It consists of a sharp needle protruding out of a propellant reservoir tank. This reservoir is heated to above 156.6 °C to melt the Indium. If a sufficiently high electric field is applied between the needle and an extractor electrode, a socalled Taylor cone is formed and ions are directly pulled out of the liquid metal surface at the tip of the needle (see Fig. III). These ions are accelerated out by the same electric field that created them. Typical emitter voltages are 6 - 12 kV for currents up to several hundred μ A. The corresponding thrust T and Isp can be expressed by:

$$I_{sp} = \frac{T}{\dot{m}g} = k_{In} \sqrt{U_E} f(\alpha) \eta_m(I_E)$$
(7)

where k_{In} =132.1 for Indium, U_E is the emitter voltage, I_E is the emitted ion current, $f(\alpha) \approx 0.90$ accounts for the beam divergence and $\eta_m(I_E)$ is the mass efficiency i.e. the fractional mass emitted as ions vs. droplets.



Fig. III: Early Indium FEEP Cluster of 4 emitters.



Fig. IV: (a) Left: Indium FEEP 1D Crown Cluster of 28 needles/emitters. (b) Right: 2D array emitter for the Ultra-FEEP proof-of-concept module.

A 1D circular "crown emitter" with 28 needles showed Isp=12,000 s while operating at 12 kV, and uses a single common extraction node making the thruster both compact and gridless (Fig IVa). It is important to note that the needles of this 1D array are constituted by porous sintered tungsten, which has been proven to be superior compared to solid tungsten for this particular application.

To meet the requirements of a rapid interstellar precursor aimed at the Oort cloud (>1000 AU), a specific impulse in the order of 50,000 - 100,000 s is needed, requiring an acceleration voltage up to 1 MV (Fig IVb).

Advanced Neutral Beam Injector (NBI) gridded ion sources are key to achieving operation at high potentials. The MITICA ion source used for nuclear fusion research on the ITER project, will use potentials as high as 1 MV to accelerate a 40 A Deuterium ion beam. These ion sources however, are designed for operational times of just minutes, limited by erosion and grid heating issues. This is not a concern with the gridless Ultra-FEEP thruster, allowing for reliable operation at voltages in the order of 1 MV and consequently the 100,000 s specific impulses mentioned. Such a propulsion system would require 4 MW of power which is currently only available from a space nuclear reactor.

In the proof-of-concept 2D arrangement shown in Fig. IVb, the emitter needles are positioned in a

hexagonal pattern, covering a surface of approximately 150 mm². For such an array of 120 needles, the performance figures are relaxed by way of selecting a mean current of 50 μ A/needle at 120 kV, producing a thrust of 3 mN with 720 W emitter power. Even at these ratings the specific power is 240 W/mN and specific impulse 30,000 s, assuming a reasonable value of mass efficiency (70%). This would be, to the knowledge of the authors, by far the highest specific impulse demonstrated by an ion thruster.

The size and scalable performance of this In Ultra-FEEP thruster make it a strong candidate for the interstellar Tin Tin mission.



Fig V. (a) Left: The JPL MiXI thrusters assembly scale comparison, (b) Right: 3U CAD drawing showing thrusters and pressurized Xenon tank.

The JPL Miniature Xenon Ion (MiXI) Thruster [14] [15] with thrust 1 mN and Isp 3,000 s will be operated by 50 W of photovoltaic panels on Vermont Tech's 9U "Ion Drive Interplanetary CubeSat" mission in July 2013, in a 500 km orbit. The assembly including the Xenon tanks is assembled in 3U package. Erosion of the MiXI's gridded extractors raises concerns for its operation in an interstellar scenario. In addition, this thruster is already slated to be space validated with substantial JPL/NASA support, so there is no need for duplication of effort.



Fig. VI: (a) Left: The Espace/MIT PETA thrusters design, (b) Right: PETA assembly scale comparison and etched micro-tips (right).

<u>The Espace/MIT AeroAstro Precision Electrospray</u> <u>Thruster Assembly (PETA)</u>, [16] can use a wide range of room temperature ionic liquids (RTIL), such as EMI-BF4 as propellant. A rugged, miniaturized assembly with no moving parts has been developed capable of providing 100 μ N max thrust in a small 1/3U package, offering Isp of 2,500-5,000 sec. When initiated from geostationary orbit the thruster, a 3U, 3 kg Cubesat is capable of reaching interplanetary space with 1.27 km/sec with a mere 128 g of propellant. The low (~15 °C) melting point of RTIL electrospray propellants such as EML-BF4 is a distinct advantage of this type of thruster.



Fig. VII: The Busek 3 cm RF Ion Thruster under testing conditions (right), showing the space qualified beam neutralizer atop of the thruster assembly (left).

<u>The Busek 3 cm RF Ion Thruster</u>, currently in development [17], delivers up to 2.5 mN thrust and Isp up to 3,000 s. For a 4 kg spacecraft, a delta-v of 4 km/s is achievable with 0.5 kg Xe, using a system power of \sim 100 W. The assembly can be housed in approximately 1.25 U.



Fig. VIII: Internal view of the Alta-Space 2U Cubesat equipped with the IL–FEEP system. The propulsion bay, the Cubesat subsystem bay and the payload sections are highlighted [18].

<u>The Alta-Space RTIL-FEEP</u> [18] belongs to the family of RTIL thrusters and has recently completed a series of vacuum lab tests. Having 3,000 Isp and a system dry mass of 700 g and 100 μ N thrust, the system could deliver a 0.5 km/s for 2U, 4 kg Cubesat for a reasonable 4 W estimated power consumption. While designed for efficient LEO station keeping and LEO to MEO transit, RTIL thruster developments could be scaled to allow planetary and deep space exploration missions in the near future.

A number of supplementary propellant-less systems are also reviewed, intended to add delta-v while the interstellar Tin Tin mission operates in the solar system.



Fig. IX: A concept rendering of an E-Sail, showing solar wind electrons reflecting off of the field produced from conducting electric tethers [19].

<u>The Kumpula Space Centre Electric Solar Wind Sail</u> (<u>E-sail</u>) was invented by Pekka Janhunen of the Finnish Meteorological Institute [20]. The system uses a number of long, thin conducting tethers maintained at a high positive potential, by means of an forward facing electron gun, to reflect solar wind electrons thus producing forward thrust via Coulomb interaction. Thrust estimates of 1 N from a 100-200 kg system have been provided for positively charged 25-50 µm wire tethers of length 10-20 km, maintained at 20-40 kV, allowing for a maximum delta-v of over 50 km/s while operating in the solar system [19].

The ESTCube-1 slated for launch 2013, is a 1 U Cubesat test mission which will explore the deployment of a 10 m conductive tether and monitor the satellite attitude changes resulting from the electric sail force. Critical to the success of this system is maintaining the angular momentum needed to maintain the tethers in their extended formation [21].

<u>The Tethers Unlimited Nano-THOR</u> concept proposes to use upper stage residual propellant spin up and release PPODs attached to tethers, with up to 500 m/s delta-v [22], essentially giving Cubesats a significant kick start into interplanetary trajectories from GSO. The concept was awarded a development grant by NASA in September 2012.

<u>Solar Sail</u> technologies can safely be described as emergent and enabling. The IKAROS spacecraft flown in 2010 demonstrated a 1 μ g acceleration using a 20 meter sail (on the diagonal) [23], which would allow earth escape from in GEO in 3.5 years.

While the useful solar flux is limited to well before Jupiter orbit at 5 AU, the inclusion of an ultra-light solar sail could provide supplementary thrust while doubling as a high-gain antenna after judicious choice of metallization of the sail surface [24]. A dual use sail of this type would have to be rigidly set and not spin stabilized per its deployment by IKAROS, because the sail structure will fold onto the spacecraft when the main high Isp thruster is engaged.



Fig. X: Depiction of the Nano-Thor concept [22]. The Cubesat is ejected in the same way an athlete performs a hammer throw.

The modelling and analysis of a Tin Tin concept employing a solar sail in the dual role of a high frequency antenna, will be developed in a subsequent study.

III.II Power Source

There have been several promising design and engineering studies demonstrating the scalability of various ion thrusters to over 10,000 Isp [25]. The availability of a high mass to power ratio power supply however, remains a key challenge for deep space and interstellar missions. The enabling technology for the deep space and interstellar missions considered here is a power source with a mass to electrical power ratio approaching ~1 kg/kWe in specific power, which is only currently approachable by space nuclear reactors.

In the context of a Cubesat mission however, where total spacecraft mass and form factor are predefined, the analysis of interstellar missions will necessarily scale with available power.

Nuclear Reactors

A historical sampling of US space nuclear reactors demonstrates a rapid improvement in the thermal to electrical efficiency of the devices, summarized in Table II [26]. Given the significant system complexity and development costs, not-withstanding the unfavorable regulatory environment, the emergence of miniaturized

space reactors for use on Cubesats before the end of the decade is unlikely. However, after 50 years of engineering experience, one may assert that the technical capability to scale space nuclear reactors down to 1 U does exist today and would be a remarkably rewarding space technology.

	SNAP-10	SP-100	SAFE-400
Date	1965	1992	2007
kWt	45.5	2000	400
kWe	0.65	100	100
Convert	Thermo-el	Thermo-el	Gas-turbine
Fuel	U-ZrHx	UN	UN
Mass, kg	435	5422	512
kg/kWe	669.2308	54.22	5.12
η(e/t)	1.43%	5.00%	25.00%

Table II: Sampling of US Space Nuclear Reactor heritage.

Miniaturized RTGs

Notable advances in Radioisotope Thermal Generators (RTGs) have supported deep space and planetary missions for many decades on missions such as such as Apollo, Viking, Voyager, Galileo and Cassini not to mention the Mars rovers of recent years [27]. The RTGs used in these missions all have relatively low specific powers less than 5 W/kg, with only the Advanced Sterling Radioisotope Generator (ASRG) providing 7 W/kg, which is used in the framing Tin Tin mission analysis described earlier in this paper (Table III).

Updating the ASRG with current materials would increase specific power to ~ 9 W/kg [28], which translates to a 2,500 year reduction in trip time to Alpha Centauri, for a current best time to the Centauri system of 22,500 years.

RTG technology	α (W/kg)	
GPHS-RTG	5.1	
MMRTG	2.8	
SRG110	3.6	
ASRG	7.1 - 9	

Table III: Comparison of existing radioisotope power sources. Specific powers refer to beginning of life (BOL) performance.

ESA is pursuing Americium in earnest as a viable alternative to Plutonium RTGs [29] [30].

The longer half-life of Americium-241 (433 years versus 88 years for Plutonium-238) requires a greater mass of fuel for a given power, however does provide the advantage of more consistent power. For the 20 year thrusting timescale considered here, the output of a 241Am fuelled system would be expected to drop by \sim 3.2%, compared to a 238Pu system which would fall

by $\sim 15\%$. Consequently the distinction between beginning and end of mission power outputs is less critical than in 238Pu systems.

The increased neutrons flux from 241Am pose a different set of problems, also. Overall, whilst the specific power of Americium RTGs is expected to be significantly lower than those listed in Table III, at ~2 W/kg, increased interest in equipping Cubesats with nuclear power sources may direct research towards miniaturized Am RTGs, appropriate for a wide number of deep space exploration missions. A similar argument could be made for Thorium reactors and RTGs.

III.III Communications

The issue of communications for an interstellar probe has been discussed by Boone et al. in the context of the Realistic Interstellar Explorer (RISE) mission [31].

In this concept, an approach is taken in which the role of the optical downlink is emphasized for data transfer and that of the microwave uplink emphasized for commands.

The conclusion from this preliminary effort is that an optical communications downlink out to 1000 AU is within the realm of technical feasibility in the near future, and it is possible to uplink a minimum bandwidth RF signal for command and data handling using a tone-tracking receiver with a very long integration time.

The total mass of the proposed optical terminal is 10 kg, which is too big to fit in a CubeSat. However recent development efforts of laser telecommunications subsystems for CubeSats by JPL [32] and Aerospace Corp. [33] suggest that the design requirements for the optical communications system of a RISE type interstellar mission can be met within the mass and power constraints imposed by the CubeSat standard. Table IV compares the performance of the RISE and the JPL 1U optical communications subsystems.

Requirements/ Constraints	RISE optical comms system	JPL 1U optical comms terminal
Max. range	1000 AU	2 AU
Pointing accuracy	400 nrad	10 μrad
Bit rate	500 bps	0.2 (62.5) kbps
Transmit aperture	1 m	6 cm
Receive aperture	4 m	11.8 m (LBT)
Mass	10 kg	~1 kg (1U)
Power	15 W	0.5 (160) W

Table IV: Comparison of the performance, requirements and constraints between the RISE and the JPL 1U optical comm. subsystems [31][32].

Further technological advancements to establish optical communications as a viable option for

interstellar nano-spacecraft include greater miniaturization of electronics and optics so that they can fit within 1U, and the development of higher power lasers and very accurate star tracking systems.



IV. MOTIVATION FOR TIN TIN INTERSTELLAR PRECURSOR NANO-SAT MISSIONS

Planetary and deep space exploration missions have only been undertaken using multi-billion dollar flagship spacecraft to date. The scientific community has recognized the versatility of Cubesat missions for interplanetary exploration and is rapidly rising to meet the challenges that the small form factor presents to the design of valuable scientific missions. As such, Icarus Interstellar is responding to the call for conceptualizing and developing outer planetary, deep space and solar system escape mission scenarios by means of Project Tin Tin.

We anticipate the sheer number of exoplanet discoveries over the past few years will culminate in the verification of an enticing Earth-like planet or moon in the local interstellar neighbourhood - ideally orbiting one of the 39 star systems which lay within 15 light years of our Sun. While the development of rapid interstellar explorers is still some decades away, the scientific community has already recognized the need for trailblazing, interstellar pathfinder missions to survey local interstellar space and Oort cloud objects.

In this paper we have outlined an idealized interstellar precursor mission using a 10 kg Cubesat, demonstrating the feasibility of the project using current technological means. In parallel to the interstellar "flagship" Tin Tin mission however, we recognize the opportunity to contribute to the ongoing enhancement of capabilities offered by Cubesat technologies by developing individual "Tins" with versatile applications.

The ultimate objective of Project Tin Tin is to be the first interstellar spacecraft to be overtaken, while future missions rush to explore our nearest star system, Alpha Centauri.

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