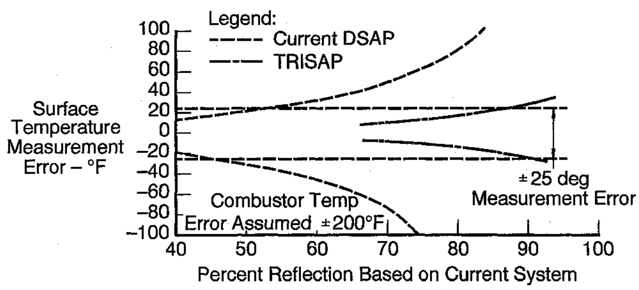

Fig. 2 Error due to variability of combustor radiance temperature.

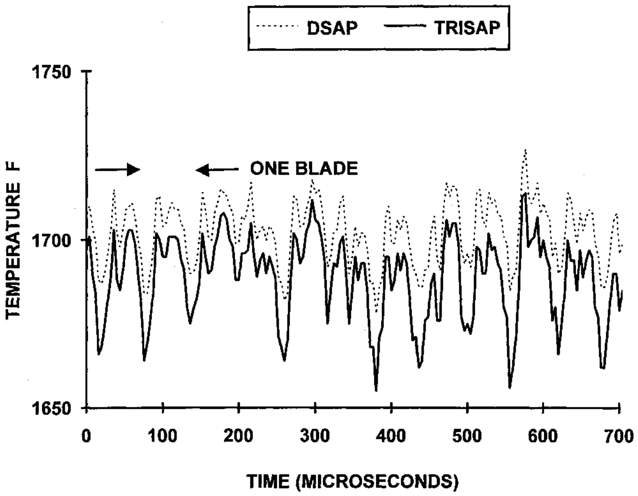

Fig. 3 Comparison of TRISAP and DSAP methods.

spectral ratios are performed until the temperatures agree within a predetermined limit selected to provide acceptable measurement uncertainty.

Figure 3 shows the results of simultaneous engine tests of the prototype TRISAP and a DSAP. The test objectives were to verify that there was no radiant contribution from the gas path in the long wavelength band and validate operability of the TRISAP system. In this test the reflection level averaged 56%, the average reflection ratio temperature calculated by the TRISAP was 4044°F, and DSAP used a conventional constant temperature correction of 4500°F. Under these conditions the DSAP will not correct the data sufficiently, resulting in erroneously high temperatures as shown in the plot.

Conclusions

Data sorting and triple wavelength pyrometry have been applied successfully to obtain on-line correction for flame in the field of view and levels of reflection exceeding 70% of input signal from a spectrally variable source. These methods provide cost-effective temperature data for turbine blade cooling development in the harsh and complex radiative environment of the first turbine, where other methods like the DSAP and thermographic phosphors have not been successful.

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Stationkeeping with Two-Way Electromagnetic Launchers

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Nomenclature

D = parabolic eccentric anomaly, rad
E = eccentric anomaly, rad
e = orbital eccentricity, dimensionless
F = effective thrust, N
G = universal gravitational constant, N-m^2/kg^2
H = hyperbolic eccentric anomaly, rad
h = specific angular momentum, N-m-s/kg or m^2/s
M = mass of primary body, kg
m = reaction mass, kg
p = semilatus rectum, m
p = momentum, kg-m/s
r = radius from the center of the primary body, m
T = time of flight from periapsis, s
v = velocity, m/s
ε = specific kinetic energy, J/kg
θ = true anomaly, rad
ϕ = flight-path angle (from horizon), rad
ω = angular velocity of the primary-secondary system, rad/s

Subscripts

m = refers to the reaction mass
$'$ = quantities measured in the launcher reference frame, as in v' for launch velocity
1 = refers to the launch point
2 = refers to the recovery point

Introduction

SERIOUS consideration of electromagnetic launchers (EML) for propulsion in space goes back to Clarke's[1] 1950 proposals for EML to launch payloads from the moon and Space Stations. O'Neill[2] provides a good summary of much of the early work and ideas in this field.

With modern computer-controlled attitude and velocity control systems on the payload, it is possible, in principle, for some kinds of EML to decelerate as well as launch payloads. A recent contribution by Forward[3] referred to a suggestion in an unpublished novel by the author to use an EML to keep a Space Station at the L1 point of the Earth-moon orbit from drifting inward-outward (the L1 point is stable with respect to E-W or N-S perturbations).

This involved sending a mass from the L1 point on a classic "free return" trajectory and catching it on the way back. This trajectory was used (in essence) by Jules Verne[4] and more recently by the Apollo 13 mission. It forms a "figure" eight shape if viewed in a frame of reference rotating with the same angular velocity as the moon (Fig. 1a). In this frame, if a mass is sent toward the moon, the EML is pushed toward Earth, both when sending the mass out and when catching it on its return. If the mass is sent toward the Earth and back on a related trajectory, the EML is pushed toward the moon.

Analysis

Figure one shows the basic architecture of the system in frame of reference rotating with the mean angular velocity of

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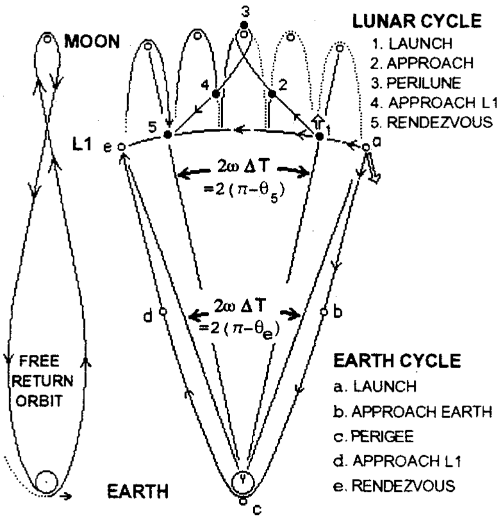

Fig. 1 Trajectory geometry for L1 stationkeeping.

the Earth-moon system. The reaction mass circulates daily on the upper lobe of the figure eight. This is an idealized approximation; variations in one-way traffic in and out of the L1 station as well as the complex nature of the lunar orbit would require frequent adjustment of the circulation schedule and trajectory.

We can demonstrate that orbits exist in this frame that return objects to their launch point using a patched conic approximation with L1 as the patch point. Assuming that the trajectory will have a periapsis radius r_p as close to the central body's radius as safety will allow, the Keplerian orbit parameters can be calculated: The specific energy $\varepsilon = v^2/2 - MG/r$; the specific angular momentum $h^2 = 2(r_p^2\varepsilon + r_pMG)$; the eccentricity $e = [1 + 2\varepsilon h^2/(MG)^2]^{1/2}$; the true anomaly (at r) $\theta = \arccos[(p/r - 1)/e]$; the semilatus rectum $p = h^2/MG$; and the flight path angle (at r) $\phi = \arccos[h/(rv)]$.

The time of flight from the L1 point to the periapsis is given by the Kepler equations[5] for an ellipse, parabola, or hyperbola, whichever is appropriate (the parabola gave a good first estimate for the Earth-moon L1 problem), as a function of ε, v, M, θ, and e as defined above:

$$\Delta T_{\text{ellipse}} = [MG/(8\varepsilon^3)](E - e\sin E) \tag{1a}$$

where $\cos E = (e + \cos\theta)/(1 + e\cos\theta)$

$$\Delta T_{\text{parabola}} = [1/(4MG)^{1/2}](pD - D^3/3) \tag{1b}$$

where $D = p\tan(\theta/2)$

$$\Delta T_{\text{hyperbola}} = -[MG/(8\varepsilon^3)](H - e\sinh H) \tag{1c}$$

where $\cosh H = (e + \cos\theta)/(1 + e\cos\theta)$.

The desired condition is for the propulsion mass to return to the L1 point. Thus, as a first approximation, the angle of rotation of the Earth-moon system during the round-trip should equal the change in true anomaly $\Delta\theta$ of the propulsion mass during the round-trip. In the symmetrical situation of Fig. 1, the Earth-moon system will rotate by $(2\Delta T)\omega$. Therefore, $\Delta\theta = 2\Delta T\omega$, or

$$\pi - \theta = \Delta T\omega \tag{2}$$

The above system of equations can be solved iteratively to yield the inertial velocity of insertion. This, of course, must be the vector sum of the actual velocity supplied by an EML and the orbital velocity of the EML, as shown in Fig. 1b. Note that in the lunar frame of reference, the L1 point circles the moon prograde once a month with an average orbital velocity of ωr, just as it circles the Earth. The Earth reference velocity is larger because, for Earth, r is larger.

Table 1 Effective radial thrust for L1 stationkeeping

	L1-moon cycle	L1-Earth cycle
Periapsis	1,738 km	7,000 km
Radius to L1	57,901 km	326,499 km
Eccentricity	0.98199	1.0164
Flight-path angle	1.363 rad	1.445 rad
Launch velocity	0.375 km/s	2.036 km/s
Cycle time	60.9 h	71.9 h
Effective thrust[a]	0.775 kN	4.229 kN

[a]For a 100-Mg mass launched and received each cycle; an equivalent rocket would have to thrust at this level for the entire cycle time.

Therefore, assuming a circular starting orbit, the components of the velocity increment supplied by the launcher are given by $v'\cdot r = v\sin\phi$, and $v'\cdot\theta = v\cos\phi + \omega r$. The resulting launch velocity is

$$v' = [(v\cdot r)^2 + (v\cdot\theta)^2]^{1/2} \tag{3}$$

Because the θ components cancel when the mass is caught again, the net radial push is due only to $v'\cdot r$. Arguing symmetry, the total recoil and capture momentum imparted by m in one cycle is simply

$$p = 2mv\sin\phi \tag{4}$$

And a mass completing one circuit would be equivalent to a rocket with F of

$$F = p/\Delta T \tag{5}$$

The above equations were entered into a TK!Solver model to generate Table 1.

In the system developed for the novel referenced by Forward, mass for ballast and shielding for the L1 station was provided by freighter spacecraft launched and retrieved by an EML on the far side of the moon, laid out between the craters Congreve and Coriolis. The reaction mass for the L1 EML was a ballasted freighter that never landed on the moon, called a "flying Dutchman," with onboard propulsion for minor orbit adjusts and the high-speed precision rendezvous at the cycle's end.

Figure 1b shows the flying Dutchman cycles in inertial coordinates, with the moon cycle at the top, (nos. 1–5), and the Earth cycle at the bottom (letters a–e). The arc represents the ideal path of the L1 point through space during the cycles. The dotted parabolic trajectory at top is what the moon cycle would look like in a nonrotating lunar frame of reference.

If necessary, the effective thrust can be increased by 1) launching at a higher velocity and using propulsion aboard the reaction mass to rotate the line of apsides of the orbit to effect rendezvous at the L1 station on return, or 2) using more frequent launches [Eq. (5) would need to be multiplied by the number of launches per cycle], and 3) using larger mass increments.

Additional Comments

Inspecting the above equations shows that, for a given central body, the function of this system depends only on r and the existence of sufficient angular velocity. This concept is thus not limited to L1 points, but can be used to exert outward pressure in any such orbit or rotating frame of reference. The central body acts, in essence, as a gravitational mirror for the reaction mass, when $r >> r_p$ (physicists will recognize this as a macroscopic version of attractive force scattering). This phenomenon might be exploited in a number of ways that could be the subject of future research.

The following suggestions presuppose EML that can both accelerate and decelerate masses with tolerable losses, and

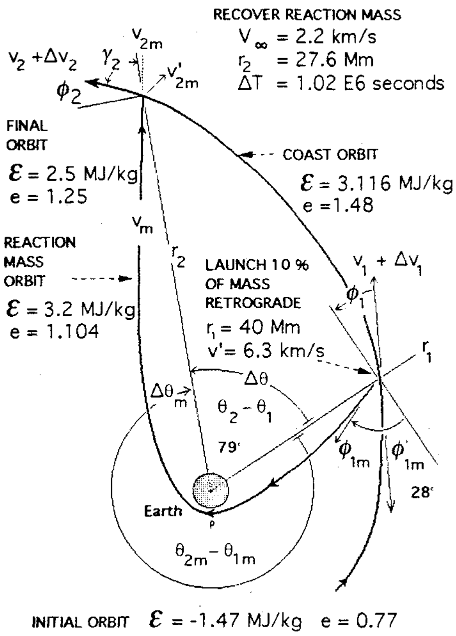

Fig. 2 Point case of net Δv with two-way EML.

that the masses ejected are "smart" in the sense that they have enough onboard computation and propulsion capability to effect rendezvous at high velocity. Forward proposed that incoming masses dock with a cradle that had been accelerated along the launcher up to the incoming velocity.[3] Alternatively, a magnet-equipped spacecraft could simply "land" on its EML "rails" roughly analogous to aircraft carrier landings (the velocities are an order of magnitude higher, but electronic reactions are several orders of magnitude higher than human reactions, and the platform is stable). After "landing," the spacecraft would be, essentially, a high-speed maglev rail coach.

From certain orbits, a two-way EML-equipped vehicle could generate significant outward velocity without loss of reaction mass—effectively using the planet as its reaction mass. Figure 2 is a point example of this.[6] The general bounds on this concept need to be defined, but one can imagine that, in addition to L1 stationkeeping, satellites could be pushed away from planets, or planets away from the sun, without loss of reaction mass—given time and an energy source sufficient to make up for the change in potential energy and any inefficiencies.

Forward[3] briefly addressed the possibility of levitation. This might be done by rotating the line of apsides at the periapsis of the orbit of the reaction mass to make the reaction mass reintercept a stationary EML. Around planets with atmospheres, this might also be accomplished by using negative lift near periapsis. In addition, gas might be collected and brought back out to the levitating EML, provided the initial velocity was high enough.

Acknowledgments

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Simple Estimation Algorithm for Performance-Seeking Controllers

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Introduction

The performance-seeking-control algorithm (PSC) is designed to continuously optimize the performance of a propulsion system. The optimization is based on a steady-state model, called the optimization model, that includes the inlet, engine, and nozzle. To account for significant deviations with respect to nominal conditions experienced by the engine during its life span (engine deterioration), or for engine-to-engine manufacturing variability, the optimization model includes a set of adjustable parameters called the engine deviation parameters (EDPs), denoted as[1–4]

$$\boldsymbol{\eta}^T := [\text{DEHPT DELPT DWHPC DWFAN AAHT}] \qquad (1)$$

where

AAHT	=	area adder high-pressure turbine deviation parameter, in.^{2}
DEHPT	=	high-pressure turbine efficiency deviation parameter, %
DELPT	=	low-pressure turbine efficiency deviation parameter, %
DWFAN	=	fan airflow component deviation parameter, lb/s
DWHPC	=	high-pressure compressor airflow deviation parameter, lb/s

By definition, for the nominal engine, $\boldsymbol{\eta} = 0$. $\boldsymbol{\eta}$ is currently estimated in flight using a Kalman filter based on a dynamic model of the engine called the estimation model.

Optimization Model of the PSC Algorithm

The optimization model of the PSC algorithm is a simplified steady-state model of the propulsion system called the compact propulsion system model (CPSM). Part of it is the engine's steady-state variable model (SSVM), which consists of a piecewise linearization of the steady-state aerothermodynamic equations of the engine around a set of base points covering the power-setting range of the reference flight condition (i.e., standard day, Mach 0.9, and altitude 30,000 ft). Each of the linear models, valid in a neighborhood of a base point, is described by the equation:

$$y = G_y u + H_y \boldsymbol{\eta} \qquad (2)$$

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