Solar Sailing
Navigating by means of “Optical Lift”
Grover Swartzlander, Alexandra Artusio-Glimpse

Rochester Institute of Technology
Center for Imaging Science // Dept. of Physics
Planetary Society Cosmos-1
(June 2005 failed launch)

2012 Launch of “LightSail-1”
32 m² mylar

John Ballentine 2006
10 m² CP-1 polyimide
(380 g/m² areal density)

- Technical Objectives:
  - Stow and Release from cubesat
    (Deployed Jan 2011)
  - De-orbit from 640 km
    (Sept 2011 -240 days)
  - Passive attitude stabilization with permanent magnets
Reflection from a Perfect Mirror

\[ \Delta k_1 = 2n_1k_0 \]

Force/Area = \( I_\text{i} \Delta k / c \) \( k_0 = 2I_\text{i} n_1 / c \)

Example: \( I_{\text{sun}} = 1 \text{ kW/m}^2, A=200\text{m}^2 \) \( \rightarrow \) 1.3x10^{-3} N

Sail Density: 1 g/m\(^2\) // Mass = 0.2 kg

Acceleration: \( a = 6.8 \times 10^{-4} \ g_{\text{earth}} \) (1.1 \( g_{\text{sun}} \) at 1AU)

\[ Q = 200\% \ (\text{Efficiency}) \]
Reflection from Angled Mirror

\[ \Delta k_1 = 2\cos(\theta)n_1k_0 \]

Area = \( A_0\cos\theta \)

- Orienting mirror at angle \( \theta \) requires torque (\( \Delta \) angular momentum)
- Reaction gyros required to change angular momentum and to hold the sailcraft stationary.
- Ikaros: 15.4° to 15.2° lift angle via reflectivity change (July 2010)
  \[ Q_{\text{lift}} \sim 48\% \text{ at } 15\° // \text{ Change in lift force: } 0.6\% \]
"The next design issue to be considered is the ability to **steer the vehicle**. When the vehicle is in near earth orbit torque rods can be used with limited capability as the orbit increases. Reaction wheels and Control Momentum Gyroscopes (CMGs) can be used for attitude control, but there is a limit to which they can be used until they reach saturation or gimbal lock. Then there must be some other means to desaturate the reaction wheel or unlock the CMG. In low earth orbit, the common method is to use **torque rods**, but these are **unusable** in the orbits in which solar sail vehicles are not affected by atmospheric drag or out in deep space. **Steerable sails give the vehicle the capability to not only provide for propulsion, but also control the attitude of the vehicle.** This method provides an alternative to desaturate a reaction wheel or unlock a CMG.
Sailing to Inner/Outer Orbits

\[ F = \frac{mMG}{R^2} = \frac{mv^2}{R} \]

\[ \therefore \quad R = \frac{MG}{v^2} \]

\[ E = -(1/2)mMG / R \]

\[ \Delta R = \pm R(\delta v/v)^2 \]

\[ v' \approx v \left(1 \mp (\delta v/v)^2 \right) \]

Venus: \( v' = 35 \text{ km/s} \)
Earth: \( v = 30 \text{ km/s} \)
Mars: \( v' = 24 \text{ km/s} \)
Stable Optical Lift.
Nature Photonics 5 (2011)
Optical Flying Carpet

An array of semi-cylindrical lightfoils create the flying carpet. With a high surface area, the flying carpet could easily be used for biological surface contact needs, and is capable of carrying large payloads in large transportation jobs.
Steering Solar Sails

Long array of particles

Incident Illumination

CM

Radiation Pressure

Force by foil array
Lightfoils: Are “Optical Wings” Possible

Kutta-Joukowski Theorem

\[ L_y = \oint p\hat{n} \cdot \hat{y} da \propto \Gamma \]

\[ p\hat{n} : \text{ Minkowski Optical Pressure} \]

\[ \Gamma = \oint (\vec{E} \times \vec{B}) \cdot d\vec{l} : \text{Circulation} \]

\[ \sim \oint E^2 \vec{k} \cdot d\vec{l} \]
Can we make an optical wing?

Vary the pressure distribution by changing the angle of attack, $\alpha$.

Will the optical wing be stable?
\[ \vec{F} = \sum_j (\delta P_j / c) (n_{2,j} \cos \theta_{2,j} (1 - R_j) - n_{1,j} \cos \theta_{1,j} (1 + R_j)) \hat{n}_j \]

\[ \vec{T} = \sum_j \vec{r}_j \times \delta \vec{F}_j \]
POV-ray simulation

Incident Rays (4,000)

"Torque"

Transmitted Rays (250,000)

δF

α

Force

Lift and Scattering Components

Note: No Gradient Force

Lift Force Perpendicular to the Incident Flow
Stable Rotational Equilibrium
Force and Torque Efficiency

\[ \vec{F} = \frac{n_1 P}{c} \left( Q_x \hat{x} + Q_y \hat{y} \right) = \frac{n_1 P}{c} Q \left( \cos \Theta \hat{x} + \sin \Theta \hat{y} \right) \]

\[ \vec{T} = \frac{n_1 P R}{c} Q_T \hat{z} \]

Desirable Attributes:

- Large Force Efficiency: \( Q > 10\% \)
- Large Lift Component: \( \Theta > 45^\circ \)
- Stable Rotational Equilibrium: \( Q_T = 0 \)
- Stiff torsional spring constant \( \left( \frac{dT_z}{d\alpha} \right)_{T_z=0} < 0 \)
Force Efficiency and Lift Angle

Semicylinder Force
Glass in Water
s-polarized

Q

Force Efficiency, Q

Force Angle, θ

Attack Angle, α

0 0.05 0.1 0.15 0.2 0.25 0.3

0 30 60 90

-100 -50 0 50 100

-90 -60 -30 0 30 60 90
Experimental Setup

- Laser: 
  - Wavelength: \( \lambda = 975 \text{ nm} \)
  - Power: 330 mW, fiber module
  - Type: Butterfly laser Diode

- Laser Filter

- Objective: 40x

- Sample Stage

- Lens: 
  - Focal length: \( f = 60 \text{ mm} \)
  - Distance: \( d = 50 \mu\text{m} \)

- Camera

- White Light

- Dichroic Beam Splitter

- Mirror

- Image inset
Fabrication of Optical Wings

Melted OIR 620 photoresist rectangles produce rounded tops forming rods with semicircular cross-sections. These semi-cylinders are released from the Si substrate they are formed on by a XeF₂ dry etchant, and then lifted from the substrate with a surfactant bath.
Lift and Scattering Forces

Lift Angle ($\Theta$) = 54.5°
Transverse Speed (Lift) = 3.5 $\mu$m/s
Levitation Speed (Scatter) = 2.5 $\mu$m/s
Two Videos Demonstrating
1. Optical Torque
2. Optical Lift
Optical Flying Carpet

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Beam of Light

Force
Fabrication of Flying Carpets

Making the Mold

1. 1 μm layer of thermal silicon dioxide grown on 6” silicon (Si) wafer
2. OiR 620 resist spun onto wafer, exposed to UV through patterned mask, and developed to leave holes in resist
3. Etch oxide exposed by gaps in resist with buffered oxide etch bath (BOE)
4. Isotropic reactive ion etching (RIE) exposed Si wafer in with sulfur hexafluoride gas (SF₆) using remaining oxide as etching mask
5. Remove remaining oxide in BOE

Making Carpets with CP1

1. Clean mold and place small piece of tape on one side of the mold
2. Spin coat CP1 resin onto mold
3. Cure in N₂ chamber oven for several hours
4. Cut CP1 film into desired carpet dimensions
This is a 20X microscope image of the first ever fabricated CP1 flying carpets. The carpet features are semi-circular with 5 \( \mu \text{m} \) radii on a 50 \( \mu \text{m} \) substrate. XY-dimensions are given in the image. Here, the carpets have yet to be cut from the CP1 film – film shown to left.
Toward Optimizing Shape

Trapezoid, Area=1, $n_2/n_1=1.2$

$h = b_1/2$

Semicylinder-like

$b_1 = 2(2/\pi)^{1/2} = 1.6$

$b_2 =$ variable, $h = 2/(b_1 + b_2)$
Progress to Date

• Numerical Modeling (forces & torques)
  - Morphology
  - Refractive Index
  - Focus on Rotational Equilibrium Conditions
  - Figure of Merit
  - Ray and Wave Models

• Fabrication
  - Photolithographic Mastering in Silicon
  - Pattern Transfer in CP1 Polyimide
  - Successful lift-off

• Single Wing Experiments
  - Optical Torque Demonstrated
  - Optical Lift Demonstrated

• Review Proposed and Past Solar Sail Missions
Near Term Plans

- Numerical Modeling (forces & torques)
  - Complex Structures (optical flying carpet)
  - Selective Coatings (e.g., metallic)
  - Comparison of Ray and Wave Models

- Fabrication
  - 2nd Generation Photolithographic Mastering
  - Thin CP1 Polyimide
  - Explore Sol-Gel or Aero-Gel Materials

- Flying Carpet Demonstration

- Identify a Target Solar Sail Mission
  - Areal Density
  - Communication Barriers
  - Unfurling Mechanism and Support Structure
  - Rotating or Fixed
  - Required Maneuvers
List of Potential Space Missions

• Near Earth Orbits
  - short duration, space debris receptacle
  - polar satellites for communication, etc.
  - Lagrange Point (e.g., L1)

• Inner Planets
  - Several Mars missions per year
  - Space weather stations (hours lead time)

• Outer Planets
  - near sun deployment

• Interstellar
  - escape velocity
  - millenium voyages
  - ultra-low density sails
Lagrange Point L1
Solar/Earth Observatory

Distance from Sun: 0.99 AU

Solar Constant: $I = 1.36 \text{ kW/m}^2$

Sail Area:

$$\vec{F}_s = \frac{m M_s G}{r_s^2} \left( -\frac{z}{r_s} \hat{z} - \frac{y}{r_s} \hat{y} \right)$$

$$\vec{F}_e = \frac{m M_e G}{r_e^2} \left( +\frac{z}{r_e} \hat{z} - \frac{y}{r_e} \hat{y} \right)$$

$$\vec{F}_s + \vec{F}_e + \vec{f}_{sail} = \left( m v_y^2 / r_s \right) \hat{z} + \left( m \dot{v}_y \right) \hat{y} + \left( m \dot{v}_z \right) \hat{z}$$

Lissajous or Halo orbits
Interstellar Probe Mission

200 m Sail Radius
Areal Density 1g/m²
Exit Velocity: 14 AU/yr
Sailcraft Mass: 256 kg
Unfurl at 0.25 AU
Rotating design
70 km/s at 5 AU
300 yr mission
400 AU range

http://interstellar.jpl.nasa.gov
Optical Lift Team

Grover Swartzlander // Alexandra Artusio-Glimpse, Timothy Peterson // Alan Raisanen

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Solar Sail Mission Applications and Future Advancements
Malcolm Macdonald and Colin McInnes, Univ. Strathclyde
2nd International Symposium on Solar Sailing, July 2010, NYC

Fig. 4 Solar sail mission catalogue application technology requirements. IHP = Interstellar Heliopause Probe; JAtP = Jupiter Fly-by with Atmospheric Probe release; MeSR = Mercury Sample Return; MeS-S = Mercury Sun-Synchronous; SbSR = High-Energy Small-Body Sample Return; SPO = Solar Polar Orbiter; VenusSR = Venus Sample Return.
Torque Efficiency & Lift Angle

Semicylinder Torque Glass in Water s-polarized

Stable Equilibrium
Eqlm Refractive Index Dependence

Force Components at Equilibrium
Semi-Cylinder, Area = 1

Semicylinder has two rotational eqlm angles. For one the lift vanishes for index ratio above 1.4. The largest lift angle, $\text{atan}(F_y/F_x) = 65$ deg, occurs at $n \sim 1.2$. The Figure of Merit, (slope of torque at eqlm) $\times$ $(F_y)$ is also optimum at $n \sim 1.2$. 

![Graph showing force components at equilibrium for a semi-cylinder with eqlm angles. The graph compares force components as a function of $n_2/n_1$.](image)
EqIm Angles of Attack

Angle of Attack at Equilibrium Angles

\[ \alpha, \text{ attack angle} \]

\[ \frac{n_2}{n_1} \]

Lift Force

- \[ \text{attack_angle} \]
- \[ |\text{force}_y| \]
Trajectory of a semi-circular lightfoil with different refractive indexes

- $m = 1.2$, $\theta_0 = -40.4^\circ$
- $m = 1.3$, $\theta_0 = -56.9^\circ$
- $m = 1.5$, $\theta_0 = -90^\circ$

Initial angle of attack, $\theta = -85^\circ$

Area = 1
Length = 1
Time = 40 s