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Solar Sail Scalability and a "Truly Scalable" Architecture: The Space Tow

Gyula Greschik*
University of Colorado, Boulder, Colorado 80309

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Solar sail scalability is often understood to be the quality that renders a structural architecture applicable to (or efficient under) ever larger global dimensions. At the heart of this definition is the impact of extreme or, rather, extremely large, dimensions on structural performance. Scalability, however, can also be interpreted as a much broader issue with far more critical importance to solar sail engineering, as the *dimensional indifference* of technologies and engineering steps that (will one day) make solar sailing a reality. Scalability, in fact, the lack thereof, in this comprehensive sense which is implied in the present work is the single most serious challenge to sailcraft engineering, hindering all major steps of development: design, fabrication, and component and system verification. The systematic review of the dimensional issues for these steps presented in this paper, therefore, offers valuable insight into engineering bottlenecks and helps to identify desirable structural and design qualities to mitigate them. These qualities are consecutively combined into an architecture, the *space tow*, which consists of a sequence of like sail elements linked with filaments. Some of the performance metrics and unique features of this design, scalable in many more ways than most alternatives, are reviewed.

Nomenclature

A	=	total sail surface area
A_c	=	filament truss longeron cross section area
A_0	=	surface area of one sail panel
A_1	=	cross section area of single filament
a, a_c	=	acceleration; characteristic acceleration
b_s	=	sail panel film nominal billow magnitude
c	=	sail panel square edge
d_1	=	diameter of single filament
E, ν	=	Young's modulus, Poisson's ratio
e_{z0}, e_z	=	boom tip lateral deflection, with linear and nonlinear approximation
F	=	thrust in the sailcraft direction
F_1	=	maximum force in one filament truss longeron
F_r	=	thrust in the illumination (sun-radial) direction
F_{0x}, F_{0z}	=	sail panel boom tip load axial and lateral components
g_p	=	technological gap between facing panel boom surfaces in stowage
h	=	sail panel boom total depth
I	=	cross section moment of inertia
L	=	space tow length, $=nl$
L_b	=	sail panel radial boom length
l	=	filament truss bay length (spacing of sail panels)
l_d	=	length of filament truss diagonal
M	=	steering torque
m	=	sail panel mass
m_p	=	mass of payload (spacecraft without the tow)
m_s	=	mass of space tow structure (filaments and panels)
m_{1p}	=	average mass of filament truss bay
n	=	number of space tow truss bays
n_1	=	number of filaments in truss longeron at base
P_e	=	panel boom Euler critical load, $=\pi^2 E_0 I_0/(2L_b)^2$
$p_{\mathrm{ef}0}$	=	maximum effective photon pressure at one astronomical unit from the sun, $=\eta_s p_{s0}$
p_{s0}	=	ideal solar light pressure at one astronomical unit from the sun, $=9.126\ \mu$Pa
T	=	temperature
t	=	thickness
t_0	=	sail panel boom reinforcing strip thickness on each side of sail
w_0	=	sail panel boom reinforcing strip width
α	=	offset angle; angle between the spacecraft orientation and the direction of illumination, cf. Fig. 1
$\alpha_{T,1}$	=	coefficient of thermal expansion
β_s	=	sag (billow) to half diameter (half diagonal) ratio
η_e	=	Euler margin of safety, $=P_e/F_{0x}$
η_s	=	sail sheet effective reflective efficiency
ρ	=	material density
φ	=	normalized location of filament attachment points on panel boom
ω	=	slope difference (radian) between the extreme panels

Subscripts

0	=	sail panel boom
1	=	space tow truss filament

I. Introduction

SCALABILITY in the comprehensive sense means dimensional indifference: the robustness of a process, algorithm, design, or technology in the context of widely varying dimensions. Issues of scalability traditionally haunt engineering at major technological steps inspired by analogies of different dimensions or, alternatively, when a given technology is applied on an ever increasing (or decreasing) scale. Solar sailing happens to combine both of these scenarios. It is gradually being realized as a technological breakthrough which, as its name suggests, is somewhat similar to sailing; a similarity that quickly proves superficial once structural details and propulsion physics are considered. The engineering of a solar sail also involves a number of traditional technologies in the context of hardware of truly extreme dimensions.

A photon sail combines microscopic component thicknesses, real-estate to urban-development size overall dimensions, loads of particle-physics magnitudes, and complex yet potentially critical

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*Research Associate, Center for Aerospace Structures, Department of Aerospace Engineering Sciences, USB 429. Member AIAA.

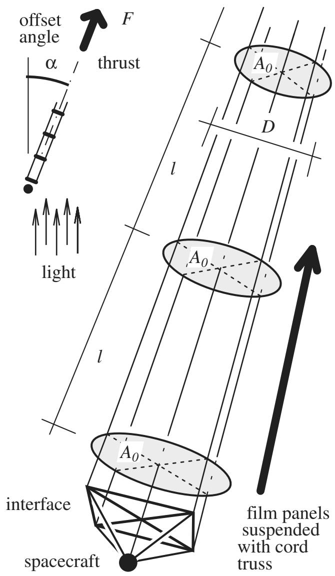

Fig. 1 Space tow concept with no filament truss diagonals shown.

nonlinear structural effects such as wrinkling. The combination of these dimensional extremes challenges all major engineering steps: design, fabrication, component and system verification, and performance optimization. One aspect of this challenge is the reliable management and prediction of the responses of large, perhaps partly wrinkled or slack, film sheets. Thus dimensional issues turn out to even impact constitutive modeling.

II. Dimensional Issues in Sail Engineering

Sail design and structural analysis are seriously challenged by a variety of dimensional issues that range from the pitfalls of “speculative intuition” (intuition not supported by direct experience) through modeling uncertainties to critical computational details. Results (designs and analytical studies) can still be produced, but with uncertain fidelity and reliability, and often at the cost of admittedly inappropriate assumptions tailored solely to render the modeling problems solvable at all. Affordable physical verification for these results is typically impossible precisely because of the dimensions involved.

Dimensional problems penalize fabrication via various sensitivity issues, handling and tooling difficulties, and by facility and procedural size limitations. These size limitations do not only call for innovative manufacturing and assembly solutions, but they also render the quality and dimensional control of the output virtually impossible.

Laboratory testing is plagued not only by dimensional limitations (what vacuum facility could host a 100-m-class sail?) but is also polluted by gravity to the point of rendering observations applicable to little more than software and computational model verification. On the scale considered, gravity can also dramatically alter wrinkle patterns and thus the membrane response itself. This unfortunate effect consequently undermines the role of laboratory testing even for software verification alone, because the condition for which analysis programs can be verified may differ from the mechanical reality of a mission environment even on the material (wrinkled membrane) response level.

Component and system verification in space, on the other hand, is very expensive, often prohibitively so, again largely because of the sizes that would be required for a meaningful test. (Biological, metallurgical, etc., and even most structural experiments in space can be conducted with *relative* ease because their validity does not require dimensions that are so difficult to manage. A solar sail, however, has to be big for a system test).

The last aspect of scalability is how sail performance depends on size. This issue will grow in significance as sailing will be a reality, its technology will mature, and ever more complex missions will be undertaken. Now, however, when not a single sail has been flown yet, the importance of performance scalability fades against those hindering the very development of the technology. Still, despite its less than pressing urgency, the performance-size dependence happens to be the most often discussed aspect of the dimensional challenge.

III. Systematic Review of Scalability Issues

Despite the well-known dimensional challenges alluded to in the preceding section, a publication to offer comprehensive insight into their causes and implications is hard to find. One reason for this silence may be that size and the way it is coped with are considered to pose a given, unavoidable conflict worth little elaboration. Contrary to this opinion, however, a systematic review could offer unique benefits: it would ferment focused public discussion on the keenest technical issues and, consequently, it may help identify solutions or strategies to alleviate or eliminate some bottlenecks. The present paper is an effort in this direction.

Carefully considering the nature of the challenges faced, some of the underlying reasons are discussed. The first of these is sheet size *and shape*. The recognition that surface shape contributes to the scalability problem is critical because it eliminates the otherwise axiomatic conflict between size and a number of scalability issues. Another key reason is the infeasibility of incremental development: the impracticality or irrelevance of subscale hardware for real-life concept, system, or component verification. This limitation may be eliminated with a modular design in which similar elements together constitute the sail but a few of these suffice for technological and performance testing. The third fundamental reason is seen to be the sensitivity of ethereal hardware to Earth-based gravity. Although no means to eliminate on Earth the pollution of tests by gravity is identified, modularity and the small size of modules are seen to reduce the seriousness of the problem on the component level. Finally, boom lengths that scale with the sail size are mentioned as undesirable for performance efficiency.

The causal skeleton thus unveiled is then used as a road map for conceptual design. A possible architecture to alleviate some dimensional problems is outlined.

IV. Truly Scalable Architecture

Directly addressing the key scalability concerns identified in the review, the concept of the space tow (a sequence of similar sail panels strung on a filament structure and hung from the spacecraft) is derived. This architecture involves no global booms. Local stiffeners, if needed at all, need only to support the very low loads within individual panels. The latter, in turn, can be small, may be fabricated in a confined space, and stack compactly for stowage with the filaments collapsed between. Geometric quality control is manageable. Meaningful incremental development and verification of the involved technologies, components, or the entire system is possible. Performance and operation are robust and fault tolerant against panel and nonsystematic cord length imperfections. The concept’s mechanical simplicity, modularity, and compact stowage may even permit its development and application as an off-the-shelf “add-on” propulsion subsystem.

To demonstrate its practicability, the derived concept is also briefly examined from an operational perspective. Some aspects of structural performance are assessed, and a few, possibly critical, engineering and operational issues are briefly touched upon.

Note, however, that the purpose of this feasibility study is not to support the space tow idea as a possible replacement of currently pursued architectures. Rather, it merely serves to show that this concept, derived from a structured analysis of scalability issues, may indeed be worth practical engineering attention.

V. Scalability of Solar Sail Architectures

The concept of *scalability* is typically addressed in the literature in two different contexts. First, it qualifies a physical phenomenon or an engineering design as directly repeatable with different dimensions, with the specifications of the replica system related to the original via rigorous scaling laws. This scalability is studied by the discipline of similitude [1–4] and constitutes a very powerful but under-appreciated engineering tool [5]. Scaling laws specifically developed to assist the analysis and testing of solar sail structures have already been put forth [6,7].

Scalability, however, is also occasionally meant as the applicability of a structural architecture to dimensions larger than first physically realized; larger without unacceptable performance loss or risk. Although this notion of scalability is used rather informally and with an uncertain quantitative meaning, it still appears quite often in recent papers [8–13] to communicate that some design solutions could be recycled in foreseeable missions with different dimensional requirements. To rescue this term from degrading into a technically meaningless marketing word, one should rigorously define *degrees of scalability* to grasp key characteristics of various performance-size relations. Then and only then could designs or architectures be compared on the basis of scalability of this sort which shall here be referred to as *performance scalability*. A definition of performance scalability shall undoubtedly focus on the weight of compression elements as a function of dimensions and loads because stability issues render such component masses to scale with degrees of nonlinearity higher than the rest. Whatever its detailed definition, therefore, this measure will well quantify the obvious fact that performance scalability is intimately related to how compression arises and is supported in the structure. If compression member lengths and loads increase with the sail size, as in square sails, then this nonlinear penalty is inescapable, albeit it can be mitigated somewhat by streamlining the force flow pattern [14,15]. This penalty can be eliminated or reduced to a (nearly) linear degree only if compression does not span global dimensions (as in various spinning designs [16–19]) or in some cases of modular construction (e.g., the hoop sail [20–22]).

However, it is not the scalability of performance but that of the technologies involved in the engineering process that most critically hinders solar sail development. Issues of scalability in this sense of dimensional robustness plague all stages of solar sail engineering, from design through system verification. In fact, the reason for the development path of this promising means of propulsion being so very long in the historic terms of space technology development [23] is mostly due to these dimensional challenges (the primary concern of the present work).

A. Scalability of the Engineering of a Sail

For a comprehensive perspective, dimensional issues critical to photon sailing are presented in the following in the context of generic engineering steps (development phases) as put forth in Table 1. (Performance scaling is included for reference.) Not all the challenges listed are equally characteristic to all designs. For example, sails for nanosatellites [18,24,25] tend to be less susceptible to fabrication and testing problems. In its entirety, therefore, the discussion to follow most keenly concerns larger sails, such as those most aggressively pursued by NASA [8–13].

Some of the dimensional challenges to be discussed are associated with inappropriate or unverified details in the mechanical, constitutive, and optical modeling and understanding of large, partly wrinkled film sheets in space. The consequent uncertainties directly affect the reliability of the models used as well as certain mechanical steps of operation (deployment). Earth-based tests can only partially answer these concerns because the very severity of gravity effects on film sheet characteristics is yet to be conclusively assessed. The body of space flight and test experience, however, grows slowly; so far, only a handful of deployment tests for large film structures have been flown [17,26–29]. The dimensional character of these issues is emphasized here on the grounds that they often arise, are rendered difficult, or entail an elevated level of risk because of the dimensions involved.

The arguments put forth are subjective to some extent; they reflect both personal experience and common engineering sense in addition to a limited amount of information available in the literature. In fact, it would not even be possible for this review to rely fully on documented examples because details of stubborn problems and development obstacles tend not to appear in publications as frequently as success stories. Furthermore, even paths to success are often shrouded in secrecy because of proprietary issues. This constraint renders the review of dimensional challenges (the subsections to immediately follow) somewhat general and short on quantitative details.

B. Design

Solar sail design (Table 1, Sec. 1) struggles with a lack of real-life experience with thin film structures of dimensions and support conditions typically necessary for photon propulsion. As a result, the intuition to guide the design cannot train on direct observations of behavior and performance; instead, it develops from Earth-based physical experience on a much different scale, from self-serving design exercises, and from theoretical and numerical considerations.

Consequently, the reliability of models and considerations becomes uncertain. Analytical skill and state-of-the-art computational tools cannot fill the void: various guiding principles and equations (“rules of thumb,” thrust models, design methodology, or back-of-the-envelope calculations [30–33]) are bound to rely on unverified, sometimes admittedly inappropriate, assumptions. Among the questionable assumptions are that of elastic film behavior (true only for membranes stretched wrinkle-free which results in high structural loads), wrinkle models that ignore or

Table 1 Dimensional challenges in solar sail engineering in general and relevance to the cord mat design and the space tow architecture (the —— indicates irrelevance, nonapplicability)

General engineering issues			Relevance to the cord mat	Relevance to the space tow
1	Design	a) intuition cannot rely on experience	high	high
		b) unverified assumptions and approximate relations	low	——
		c) uncertain deployment loads and failure modes	high	low
2	Analysis	a) extremely ill-conditioned numerical systems	high	low
		b) inappropriate, complex, or unverified film models	high	——
		c) high cost and questionable value of transient studies	high	low
3	Fabrication	a) assembly and storage of large components	high	——
		b) material and geometric quality control	high	low
		c) damage sensitivity (physical robustness)	high	——
4	Laboratory testing	a) size limitations	high	——
		b) gravity compensation is poor on the scale of interest	high	high
		c) gravity may affect the membrane response itself	high	——
5	System verification	a) subscale hardware may be nonrepresentative	high	——
		b) expense of access to space	high	low
6	Mission performance	a) boom weights penalize large systems	somewhat mitigated	——

crudely approximate the flexural stiffness and damping of wrinkle film areas, and illumination thrust models unverified for partially wrinkled sheets in weightlessness.

Careful design can limit some of the modeling uncertainties. Unambiguous load paths can be defined, for example, by a mechanically streamlined structural skeleton as achieved in Greschik's cord mat concept [14] used in the Encounter [34] project and its technological heir [8–10], or via controlled (shear-compliant [35–37]) membrane support and loading. However, such solutions only mitigate, not eliminate, the questions.

The plague of unverified assumptions, of course, does not imply a shortage of sail design concepts [20,22,23,38,39]. It, however, affects the reliability of how these designs can (or could) be engineered. The problem is more than that of the accuracy of response or performance prediction. Certain spacecraft operations, such as deployment, are complex enough that the intuitive recognition and basic assessment of the related loads and failure modes may easily prove insufficient.

C. Analysis

The role of analysis (Table 1, Sec. 2), often a part of the design loop, is to scrutinize a construction already pinned down. Accordingly, it relies on intuition not in the creative, but in the interpretive sense: it calls for the intuitive understanding of mechanical and numerical processes to explain and diagnose quantitative details. However, for solar sails, the numerical side of this task typically takes precedence over the mechanical one because the dimensional extremes often so badly ill-condition the numerics that it takes great skill to generate results at all, let alone to guarantee, or even reliably assess, their fidelity. Numerical analysis even in the static context can easily break down because dimensional extremes badly ill-condition the problem.

The typical source of the problems is the stiffness matrix, the cornerstone of most finite element calculations. If the key terms (the pivot elements) of this matrix greatly differ in magnitude, which is the case for representative solar sail models, then number crunching can become unstable. (Even the quasi-static solution of relatively simple sail structures with a linear film model is often problematic.) Although there are methods such as dynamic relaxation [40,41] for the robust solution of virtually any problem without the direct inversion of the stiffness matrix, these can be costly and are not readily available in many finite element programs. Therefore, the analyst is typically forced to painfully manipulate numerical control until some solution is produced or, often, to also "tweak" the model itself by introducing rudimentary simplifications and assumptions into wrinkle mechanics, environmental and loading conditions, as well as dynamics. The reliability of the results so produced keenly balances on the simplifications so made, much more so than in case of design, because its purpose of high fidelity scrutiny dooms analysis to be more sensitive than design to modeling details, even if the analyst is keenly aware of this problem [42–44]. The reliability of the output suffers; uncertainties of unknown severity infect the results.

Note, however, that the preceding concerns do not render numerical analysis futile or inappropriate. Performance trends, design methods, and basic mission strategies (e.g., for maneuvering or control) can be well formulated or verified with approximate numerics [45]. Also, trust in the latter for detailed analyses can be greatly improved via comparison with tests [44]. However, questions regarding the actual impact of weightlessness on large films sheet response still remain.

Yet another analytical challenge is the simulation of transient conditions which are often affected by modeling details more profoundly than static results. Furthermore, numerical ill-conditioning renders such analyses even more expensive than otherwise (especially for implicit direct time integration) and the intuition that biases the analyst to accept or suspect a result is questionable in the realm of the transient behavior of large sail sheets. A final problem with transient analyses is that their necessary depth of detail is, again, uncertain.

D. Fabrication

Fabrication methods and issues, Sec. 3 in Table 1, tend to be proprietary more than any other aspect of sail engineering. Even the know-how of material handling is a closely guarded secret: publications even with some suggestions on how to assemble and seam large film sheets are rare [46]. However, it can be generally stated that the fabrication challenges are typically dimensional. Handling, assembly and storage, quality control, as well as damage sensitivity issues are all closely linked with the typically extreme dimensions and ethereal qualities of solar sail hardware.

It is important to recognize that the severity of these issues are due not only to the size, but also to the shape, of the components. Long elements (e.g., film strips) are much easier to deal with than long *and* wide (two-dimensional) sheets; one needs only to recall images of the giant rolls where, in the paper industry, continuously fabricated immense lengths of paper are stored. The blades of a heliogyro [16] are easier to assemble, handle, and store, than large square sail sheets.

The preceding points hold for quality control issues as well. In fact, typically not even an arbitrarily chosen small area of a large, folded sheet can be neatly and easily unfolded for inspection without disturbing or unfolding the rest, whereas such a task may be possible for a linear component. Besides, methods of geometric and material quality assurance and control for strips, booms, or cords may even be imported or adapted from other industries.

E. Laboratory Testing

The challenge of sheer size for handling and stowage is even more problematic in the context of laboratory testing (Sec. 4 in Table 1) than during fabrication because manufacturing can, in some cases, proceed with only the part of the hardware "deployed" where the assembly process is active. Further, testing calls not only for sufficient hardware support (this is true for fabrication as well) but also for instrumentation and some level of simulation of the mission environment.

A uniquely problematic issue in the simulation of mission conditions is gravity offloading: specimen support that does not interfere with the free–free dynamics experienced in orbit. Although advances continue to be made in the quality of gravity compensation [47], sail sizes are so large and weights are so low that apparatus with qualities to not interfere with specimen dynamics remains a distant hope. Test programs [9,10,12,44] must progress with this compromise, which can be indirectly alleviated somewhat by accompanying analytical work. However, even if analysis results perfectly match the test, full confidence will not be possible to establish until the influence on gravity on large membrane sheets is not fully understood and quantitatively evaluated.

F. System (Space) Verification

No information on sail system verification (Table 1, Sec. 5) is available because the only publicized project to reach this level of maturity, the Planetary Society's *Cosmos 1* sail, had been destroyed by a launch vehicle failure before even reaching orbit [48]. Other flight verification efforts have so far focused only on film surface deployment, with reduced gravity *KC-135* tests [20] performed in cooperation with the NASA Reduced Gravity Program (NASA Lyndon B. Johnson Space Center), high altitude balloon experiments [27], or in space [17,28,29]. The problem, the cost of access to space, can become prohibitive because of the sail dimensions required for meaningful system verification. (This limitation is not so severe for sails developed for nanosatellites [18,24,25]. However, experiments to verify even such designs are not small in comparison to initial tests required to begin the incremental verification of other space-based engineering or scientific technologies).

Photon sailing suffers from the need for a high initial (technical and financial) investment that would allow the accumulation of real-life experience to begin. This is due to the extreme geometric and mechanical conditions to be negotiated by any representative piece of hardware.

G. Judging the Scalability of a Design

The aspects of dimensional robustness just outlined offer a systematic approach to the rating of the true scalability of a sail design: the individual evaluation of each aspect of scalability as illustrated in the last two columns of Table 1. The first of the two columns addresses Greschik's cord mat concept [14], the other the space tow, as derived next.

For the two designs used in the illustration, the relevance of each type of dimensional challenge is highlighted. The only two scalability issues not highly relevant for the cord mat concept are those of unverified preliminary design assumptions and the boom weight penalty, entries 1b and 6a. The former is not a major concern because the cord mat structural skeleton has been specifically streamlined to eliminate major elements of uncertainty in wrinkled membrane mechanics [14]. However, the concern of the analytical assumptions of film modeling, entry 2b, is still deemed acute because analysis is judged by a higher standard of fidelity than preliminary design.

Entry 6a in the table for the cord mat design is marked *somewhat mitigated*, rather than *high*, because the way the cord mat booms are loaded approximates the theoretical optimum [15]. The order of nonlinear dependence of this boom mass penalty on overall size, therefore, is somewhat lower than for its alternative also currently pursued [11–13] (nicknamed [11] M^4) where the booms are tip loaded. The latter design, therefore, would receive a *high* grade in line 6a. Other than this, it would rate identical to the cord mat. Apparently, neither the cord mat, nor the M^4 sail is particularly scalable, albeit the former is slightly more so. (However, as shown in related publications [8–13], they are both likely to be applicable to several foreseeable missions; their *performances* are scalable within the bounds of these missions.)

VI. Deriving a Truly Scalable Architecture

The systematic review in the preceding section of the dimensional challenges allows one to not only rate and compare the scalability of specific design concepts, but it also enables one to identify architectural criteria for solar sail scalability in general. These criteria are outlined next with two key considerations in mind: the need for dimensional indifference, and that for the physical (manual) manageability of sails of various dimensions, across all stages of the development process. Once the qualities desirable for a truly scalable architecture are so pinned down, a structural concept to satisfy them, the space tow, is derived.

A. Desirable Architectural Qualities for Scalability

From the list of scalability issues reviewed, it appears that for solar sail engineering technology to be scalable, the architecture, first, should involve no large film sheets. (Indeed, it is the extreme dimensions of a large sheet that keep the engineering steps from being dimensionally robust; keep them from being cost-efficiently applicable to real hardware of various sizes.) Consequently, the surface area necessary to harvest sufficient photonic propulsion should be linearly structured: it should be constructed either of long strips or from individual sail elements linearly arranged. Such linear construction could, potentially, eliminate most fabrication and many quality control and testing problems. It may also permit the development of easily verifiable theoretical or empirical constitutive and other modeling relations that could eliminate concerns about numerical analyses.

Beyond its linear construction, the reflective surface of a scalable architecture should also integrate with the spacecraft in a manner to preserve key deployment, propulsive, and navigational characteristics regardless of the dimensions or the scale of application. By this quality of scalability, deployment and space flight tests could commence with moderate initial investment; yet they would still offer a payoff of experience directly relevant to sails large and small. Cost-effective opportunities to gain real-life feedback and operating experience would invaluably boost and give credit to development and application efforts on all levels.

For performance scalability, compression over large spans should not arise; this would permit the avoidance of long compression components (beam columns, booms, straight or curved spars) which would disproportionately penalize system mass if overall dimensions were increased. Compression components with loads and dimensions not to increase with the total surface area are still acceptable.

The last two criteria (construction to directly apply to a variety of sail sizes and compression elements of fixed lengths) suggest a modular structure: a set of individual modules functioning as sails by themselves, interconnected to exert thrust together if necessary. Module size should preferably be on the human scale. (Note that the modular construction envisioned in the hoop sail project [20–22] is not acceptable here because it integrates the modules into a two-dimensional sheet which is undesirable by the first criterion spelled out previously).

B. Eminently Scalable Concept: the Space Tow

The qualities listed in the preceding section as desirable for sail scalability naturally lead to the definition of an architecture with a set of like sail panels above one another, interconnected and suspended from the spacecraft with a filament truss which is kept taut by the propulsion itself. This concept, herein called the space tow, is a modular, linear structure with only tension elements (filaments) spanning the global dimensions, Fig. 1. Sail element size and shape can be selected to accommodate fabrication or performance concerns, without affecting the convenience of stowage in a compact stack with the filaments collapsed between the panels. Each panel needs to laterally support only the portion of the thrust corresponding to its surface area. Navigation may rely on the relative positioning (controlled offset e_p) of spacecraft and tow which begets an inertial torque M (Fig. 2) according to

$$M = e_p m_p a \tag{1}$$

$$a = F/(m_p + m_s) \tag{2}$$

Panel design, fabrication, and testing can proceed independent of the overall structure; the global response is decoupled from internal panel mechanics, provided that panel deformations under photonic pressure are small. Consequently, membrane modeling issues and uncertainties do not interfere with overall structural design and analysis. Panel reinforcement, if necessary to ensure sufficient local support against lateral photonic pressure, can be realized individually for each panel with truly ethereal means: spars of microscopic cross sections, a microtruss layer, grooves, etc. The associated weight and dimensional penalties are small, and they do not accumulate nonlinearly with the tow length.

As the membrane does not need to be folded for stowage, it can remain wrinkle-free. The structure has the potential to self-deploy once the first panel is separated, because the latter is then moved onward by light pressure, moving the next panel off the stack, etc. Panel separation may occur passively (as long as the panels do not stick to one another) or it can be actively aided with membrane outgassing or with extra "separation" material layers between the stacked panels. This deployment mechanism, including its material and mechanical details, involves the same challenges regardless of panel size and tow length. Accordingly, the concept is eminently

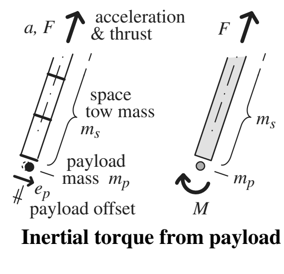

Fig. 2 Inertial torque from payload offset.

scalable even in the context of space system verification, permitting initial tests with only a few small panels to be fully representative of many key technological details of full-size structures.

The concept also lends itself to innovative solutions which can be easily developed and tested because the entire system can be stowed as fabricated on a table top. For example, fabrication on the stowage stack itself via deposition techniques or some other means can also be considered, entirely sparing the need for the handling of individual panels.

The last column of Table 1 summarizes these scaling qualities of the space tow within the framework of the rating system defined previously. Clearly, the tow concept is immune to many concerns that plague the development of many other solar sails. Of those remaining, most bear only low relevance to the design. Only two of the general concerns remain keen: risk of speculative design intuition, and gravity compensation for laboratory testing. The first of these concerns is significant because the response of the deployed tow, a likely miles' long featherweight structure, is well beyond traditional engineering experience. The dynamics and control of such a design must be carefully considered.

The space tow is superbly scalable compared with the cord mat which is a design already the best in its class, the square sails. In fact, the space tow is a truly scalable design, whereas the cord mat is not.

1. Structural Feasibility

Although the space tow concept is put forth primarily to illustrate the benefits of a structured study of scalability, the value of this exercise lies in the reasonable practicability of its output. This practicability is probed here in a preliminary manner with a simple feasibility study wherein a few structurally critical aspects of the space tow are addressed. To this end, a couple of point designs are established in a rather arbitrary manner. No attention whatsoever is paid to optimization or to advanced material and structural options; the design parameters are taken simply to be reasonable. The analysis involves a number of rudimentary approximations, all conservative in terms of sail performance metrics. Accordingly, the "design study" to follow should be considered no more than a back-of-the-envelope upper-bound assessment.

Begin by defining the sail panels as square sheets with diagonal reinforcing "booms," with a formal similarity to square sail designs [8–13]. (A number of alternatives, e.g., a hoop sail unit [20–22], could also be used instead.) Let the sail sheet be $t = 1$ μm thick-coated Mylar (Young's modulus $E = 5$ GPa, density $\rho = 1390$ kg/m^3) with $\eta_s = 0.7$ effective reflective efficiency. The net ideal solar light pressure at one astronomical unit (AU) from the sun, $p_{s0} = 9.126$ μPa, would thus load with an effective pressure $p_{\text{ef0}} = \eta_s p_{s0} = 6.388$ μPa the film if the latter were oriented normal to the incident light.

Further assume an offset angle $\alpha = 30$ deg from the direction of light, Fig. 1, and a total sail area of $A = 10{,}000$ m^2. Provided full illumination for each sail panel the thrust in the directions of the tow and of the illumination thus becomes

$$F = A p_{\text{ef0}} \cos^2\alpha = 47.911 \text{ mN} \approx 0.1723 \text{ oz} \tag{3}$$

$$F_r = A p_{\text{ef0}} \cos^3\alpha = 41.493 \text{ mN} \approx 0.1492 \text{ oz} \tag{4}$$

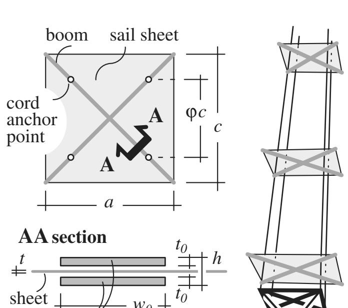

Fig. 3 Panel construction.

respectively, according to the cosine square [23] and cosine cube [15] laws.

Let the reinforcement constituting the panel booms consist of uniaxial composite strips (Young's modulus $E_0 = 350$ GPa, density $\rho_0 = 1400$ kg/m^3), one attached to each side of the film sheet. Further, include an approximately 6 μm gap between film sheet and reinforcing strip allotted for the attachment, Fig. 3; a nominal technological gap on both sides of the sheet (filled, e.g., with an adhesive). Calculate the boom properties from the reinforcing strips alone, the out-of-plane cross section inertia of which thus becomes

$$I_0 = [h^3 - (h - 2t_0)^3] w_0 / 12 \tag{5}$$

For the mass calculation, however, the material filling the technological gap is not ignored but is assumed to have the same density as the reinforcing strips. The sail panel mass is thus

$$m = A_0 t \rho + 4 w_0 (h - t) L_b \rho_0 \tag{6}$$

where $L_b = c/\sqrt{2}$ is the panel boom length.

The continuous connection between boom and sheet ([15], Fig. 1b) provides a load path for the sheet support loads somewhere between the theoretical optimum [15] and the case of four triangular quadrants suspended by their corners from the boom tips and bases [11]. For simplicity, however, the model used here is more conservative than either of these: the square sheet is assumed to hang from the boom tips only, Fig. 4.

According to this model, the component F_{0z} of the boom tip force perpendicular to the film panel is one quarter of the thrust $F_0 = A_0 p_{\text{ef0}}$ exerted on the panel:

$$F_{0z} = A_0 p_{\text{ef0}} / 4 = c^2 p_{\text{ef0}} / 4 \tag{7}$$

Applying a parabolic approximation of sag to the film billow, the boom tip force axial component can be written as

$$F_{0x} = F_{0z} L_b / (2 b_s) = F_{0z} / (2 \beta_s) \tag{8}$$

$$\beta_s = b_s / L_b \tag{9}$$

The boom Euler safety margin then becomes

$$\eta_e = P_e / F_{0z} = 8\pi^2 E_0 I_0 b_s / \left(L_b^3 c^2 p_{\text{ef0}} \right) \tag{10}$$

Consequently, the linear and nonlinear assessment of the lateral boom tip deflection are, respectively,

$$e_{z0} = F_{0z} L_b^3 / (3 E_0 I_0) \tag{11}$$

$$e_z = e_{z0} / (1 - 1/\eta_e) \tag{12}$$

where Eq. (12) is the standard relation, here expressed using the Euler margin, to account for geometric nonlinear effects by scaling the linearly calculated lateral deflection in a compressed member.

Equation (12) overestimates panel boom deflections not only because the model on which it is based is grossly conservative in terms of the sheet suspension mechanism assumed, but also because of the way this model defines external panel (boom) support. In particular, the booms are assumed to be fixed at their bases, Fig. 4, rather than suspended at an intermediate location along each, defined

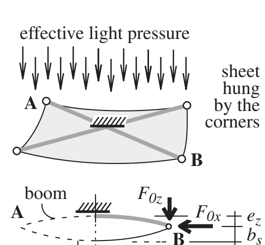

Fig. 4 Conservative model for panel deformation assessment.

in the actual design with the parameter $\varphi = 0.62$ (Fig. 3). [To minimize deflection, this parameter would need to be optimized; the optimum should be somewhere within the $\varphi\epsilon(0.55, 0.69)$ range.] System acceleration, also ignored in Eq. (12), further reduces panel deformations by inertially reducing the effective loads.

The design of the filament truss, of carbon fibers [Young's modulus $E_1 = 450$ GPa, density $\rho_1 = 2000$ kg/m^3 ([49], T75 fiber), and coefficient of thermal expansion $\alpha_{T,1} = 0.5$ ppm], be governed by a stringent stiffness criterion: permit an $\varepsilon_c = 1$ ppm maximum strain for each longeron; 1 cm elongation over 10 km (6.21 mile) of space tow length. Allow this strain to develop under a hypothetical longeron force extremum of half the total thrust, Eq. (3) (inertial relief is again ignored). The minimum longeron cross section at the spacecraft required by this strain limit is

$$F_1 = F/2 = 23.956 \text{ mN} \tag{13}$$

$$A_c = F_1/(E_1\varepsilon_c) = 0.05324 \text{ mm}^2 \tag{14}$$

If the longerons at the tow base are composed of $n_1 = 40$ filament strands each, then the cross section area and diameter of each strand becomes

$$A_1 = A_c/n_1 = 1.331 \times 10^{-3} \text{ mm}^2 \tag{15}$$

$$d_1 = 2\sqrt{A_1/\pi} = 41.17 \ \mu\text{m} \approx 1.62 \text{ mil} \tag{16}$$

Let all truss members be constructed of various numbers of filament strands of this cross section.

Let the number of longeron filaments linearly decrease from tow base to tip, and make the truss diagonals (four between adjacent panels, one on each truss side; not shown in the figures) generally contain one-third of the number of filaments in the corresponding longerons. As the length of each diagonal (cf. Figs. 1 and 3) is

$$l_d = [(\varphi a)^2 + l^2]^{1/2} \tag{17}$$

the average mass of all cords for one panel (the average mass of the cords between adjacent panels) is

$$m_{1p} = 2(l + l_d/3)A_c\rho_1 \tag{18}$$

In stowage, let the panels, stacked on top of one another, accommodate a $g_p = 50.8\ \mu$m $= 2$ mil technological gap between the facing boom strip surfaces. The filament diameters, Eq. (16), can fit in this gap if and where they are laid in the stack across and between the boom strips. The bulk of the filament truss, however, as well as components to attach it to the panels, can easily fit in the much larger gap between the unreinforced areas of the panel film sheet faces. This gap may also accommodate (be filled with) some material to escape in space in gaseous form (plain air may also be an option). This can facilitate panel separation during deployment. With n denoting the number of panels, the stowage stack height H is thus

$$H = n(h + g_p) \tag{19}$$

$$n = A/A_0 \tag{20}$$

Finally, consider the space tow thermal bow which results from the temperature difference across the filament truss, a gradient likely unavoidable due to the uneven shading of the filaments by the panels. This bow is uniform along the space tow, resulting in a relative angular rotation between the tow ends. Let this rotation between tow tip and base be no more than $\omega_{\max} = 0.1 = 5.73$ deg, a rather stringent limit. Given the filament properties listed, this kinematic criterion is satisfied if the temperature difference across the smallest truss cross section dimension is not greater than

$$\Delta T_{\text{cr.s}} = \varphi c\omega_{\max}/(L\alpha_{T,1}) \tag{21}$$

2. *Two Point Designs*

The constraints and relations outlined so far are here put into the contexts of two point designs: one with $c = 1.0$, the other with $c = 2.0$ m panels. Selected specifications and performance metrics for the two (beyond those discussed in the previous section) are presented in Table 2.

As the total surface area is pinned down as the same for both designs, the $c = 1$ m design entails four times as many panels as the $c = 2$ m one. The bay lengths, however, need to be greater in the latter case to ensure full panel illumination with the given $\alpha = \pi/6$ offset angle. As a result of these conflicting effects, the ratio of the tow lengths between the two designs is not four but two; the length of the $c = 1$ m tow is a little more than 24 km, as opposed to the 12 km for the other case (15.2 and 7.6 miles, respectively).

The panel booms perform well, offering a comfortable margin of safety against Euler buckling and small tip deformations. As alluded to before, these numbers are very conservative: a realistic analysis of the actual mission conditions would verify structural sufficiency with a much wider margin.

Although neither design is aggressive in terms of structures technology and neither has been optimized in any way, neither much exceeds 3 g/m^2 surface specific mass, a favorable figure for a 10,000 m^2 sail. Stowage is simple and moderately compact: less then 3 and 1.3 ft depth over a 1 or 4 m^2 footprint, respectively. This may enable tabletop assemblage and stowage.

The difference between the designs in terms of the temperature gradient permissible across the truss for the maximum 0.1 rad = 5.73 deg tow tip dip is 20.3°C for the larger vs 5.1°C for the smaller panels. These numbers are rather stringent: they do not indicate robust thermal-dimensional performance. However, both the thermal expansion coefficient ($\alpha_{T,1} = 0.5$ ppm) used for this assessment [Eq. (21)] and the actual thermal conditions of the fibers in space (exposed to space on all sides but stretched between reflecting and shading sheets) are uncertain. It is, therefore, yet to be seen how serious a challenge these numbers indicate for the fabrication and operation of real hardware. Because of the scalability of the concept, however, it would be possible to answer incrementally (and with gradually accumulated flight experience) this and other important questions alluded to in previous sections. The results in Table 2, however, sufficiently demonstrate by themselves the structural feasibility of the concept.

Table 2 Comparison of point designs

Specifications and parameters	Symbol	Panel size 1 m^2	4 m^2	Unit
Specifications:				
Panel edge	c	1	2	m
Total boom thickness	h	36	99	μm
Boom strip thickness	t_0	11.50	43.00	μm
Boom strip width	w_0	6.350	4.763	mm
Geometric characteristics:				
Panel spacing	l	2.449	4.899	m
Number of panels	n	10,000	2500	——
Tow length	L	24,495	12,247	m
Panel structural design:				
Flexural stiffness	E_0I_0	8.234	134.5	N · mm^2
Euler load	P_e	40.63	166.0	μN
Euler safety margin	η_e	2.714	2.771	——
Tip defl. linear upper bound	e_{z0}	17.1	33.6	mm
Tip defl. nonlin. upper bound	e_z	27.1	52.5	mm
Mass performance:				
Mass of one panel	m	2.270	9.256	g
Average truss bay mass	m_{1p}	0.701	1.402	g
Sail specific mass	ρ_{srf}	2.971	2.665	g/m^2
Stowage:				
Stack height	H	0.868	0.375	m
Thermal performance:				
Max. temp. diff. across truss	$\Delta T_{\text{cr.s}}$	5.1	20.3	°C

Characteristic acceleration is mission-specific because it also depends on the payload (spacecraft) mass. If the latter is, say, 50 kg, this performance index at 1 AU in the tow direction is $a_{c1} = 0.599$ and $a_{c2} = 0.625\ \text{mm/s}^2$ for the two designs, respectively.

3. Feasibility: Concept vs Reality

According to the parameters presented in the preceding section, the space tow architecture may not only be feasible, but also attractive; not only in terms of the scalability of development, but even in terms of performance. However, one should not rush to such a conclusion prematurely. The performance metrics presented indeed prove "back-of-the-envelope feasibility" but actual, real-life practicability can only be proven with real-life experience or, until the latter is available, with extensive design, analysis, fabrication, and component and subsystem testing. These engineering steps must pay as careful attention as possible to all conceivable operational scenarios which greatly differ for the space tow from "classic" architectures such as square designs or the heliogyro. The deployment of the first panel (after which deployment is self-powered), failure modes associated with shading, navigational strategies, and dynamics are just a few of these issues. These and other operational challenges are not less daunting than other challenges for other sail architectures. However, the space tow offers the possibility of combating its own problems incrementally and cost-efficiently, without being forced to accept unaffordable management and financial risks; it renders the engineering process more scalable and dimensionally robust than most other sail designs.

VII. Summary

It has recently become rather common to claim various solar sail architectures to be scalable based on their ability to offer acceptable performance for a number of foreseeable missions that call for different sail sizes. This sort of scalability, however, would be of secondary significance even if a general method for its quantification were rigorously defined. The scalability challenges of prime, in fact, critical, concern to solar sailing are those of the engineering development process itself: bottlenecks and issues related to the extreme dimensions involved. The present paper has offered a systematic review of these problems which seriously handicap all major engineering steps from design through fabrication to testing and verification. The structured approach followed naturally led also to the definition of a solar sail concept distinguished by the scalability not of its performance but of its engineering; a scalability that may enable cost-efficient and incremental development. A preliminary feasibility study has also revealed that, for sails in the $10,000\ \text{m}^2$ class, this concept may easily feature less than $3\ \text{g/m}^2$ surface specific mass; this entails an $a_c \approx 0.6\ \text{mm/s}^2$ characteristic acceleration for an assumed 50 kg net spacecraft mass.

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D. Edwards
Associate Editor