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Space-as-a-Service: A Framework and Taxonomy of -as-a-Service Concepts for Space

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Abstract

The servitization of space is introducing profound change, challenging established companies with new business models, and significantly lowering the entry barrier to space. New types of services such as Mission-as-a-Service, Satellite-as-a-Service, Constellation-as-a-Service, etc., are introduced. However, what these notions mean is not clear and in practice, they are often used with contradicting meanings. This paper aims to provide an initial survey of various new service concepts in the space domain and develops a taxonomy and framework for classifying these emerging services with their underlying systems. A particular emphasis is put on distinguishing novel, "New Space" services from traditional space services. We find that these new space services differ, compared to traditional space services in at least three aspects: New space services have their origin in a transition from a product- to a use-oriented business model and make reference to Cloud computing and its underlying techniques such as virtualization. We conclude that analogous to the terrestrial impact of Cloud computing on the emergence of numerous e-commerce start-ups, we might see a similar surge of in-space applications, building on a new space service backbone. Such a development is likely going to be enabled by the shift from traditionally high capital expenditures of developing space applications to operating expenses, thereby lowering the entry barrier.

Keywords: servitization, space-as-a-service, product service system, system architecture, systems engineering

1. Introduction

Space services are not new and exist since the emergence of commercial spaceflight, for example, in the form of earth observation, telecommunication, and navigation services. However, more recently, new space services are emerging, which differ from the existing ones. "-as-a-Service" services are increasingly proposed by companies. An example is payload hosting: Loft Orbital and multiple CubeSat companies (ISIS, GomSpace, NanoAvionics) enable the launch and operation of a payload. The development of customized spacecraft buses for each payload is no longer necessary as long as the payload is built against a standardized interface.

As the example of payload hosting shows, these new space services are replacing traditional, product-centric business models and transforming them into "-as-a-Service" business models. Similar to terrestrial services, a win-win situation for customers and service providers may be created [1]. For the customer, the capital expenditures are drastically reduced as large parts of design, development, manufacturing, etc. are no longer necessary. Instead, the cost is shifted towards operating expenses, and incurred during the use phase of the service. For the service provider, larger profit margins are possible, due to a more efficient approach to providing the service and exploiting learning and economy of scale effects [2]. However, specifically in a space context, customers can also outsource the compliance assessment with government regulations, insurance, licensing, launch integration or space data delivery to the service provider.

Nascent new space services are, for example, hosting multiple software applications by customers on a single spacecraft. ESA's OPS-SAT mission prototyped this concept: More than 100 companies and institutions have applied to uploading their algorithms to a 3U-CubeSat for testing them in space [3]. New technologies such as edge computing and 5G in space enable unprecedented processing and transmission of data in space, potentially leading to a surge in new space services, backed by an in-space infrastructure [4], [5].

While these new space services have a rapid impact on the industry (payload hosting is offered by most CubeSat suppliers), a deeper understanding of these services is missing, for example, what types of services exist, how they differ, and what the constituent elements are. To our best knowledge, except for Kulu [6], no survey paper exists that analyses new space services in detail. While Kulu [6] considers certain new space services such as payload hosting and Constellation-as-a-Service, the paper's scope is limited to constellations. The majority of publications in this area are company websites or blog posts describing these new service offerings.

Also, seemingly overlooked by the literature, the substitution of space products by space services may also lead to significant sustainability benefits such as a reduction of spacecraft launched and thereby a reduction of space debris generation.

As a first step in addressing these gaps, this paper presents an initial taxonomy and framework of new space services with a focus on "-as-a-Service" concepts. We start with a brief survey of these services in the literature in Section 2 and present a taxonomy in Section 3. Section 4 presents an initial framework. We conclude with a discussion in Section 4 and Conclusions in Section 5.

2. "as-a-Service" Concepts: A Survey

"-as-a-Service" concepts are numerous and many concepts linked to space mission design have been proposed as an "-as-a-Service". Figure 1 provides an overview of these concepts with abbreviations if they were found in the literature. We will explore these concepts in the following by subdividing them into those related to the space- and ground segment, and those including both segments.

As mentioned in the introduction, an interesting observation from the survey is that most references to these services are from company websites instead of academic papers, indicating that the current trend is driven by industry rather than academia.

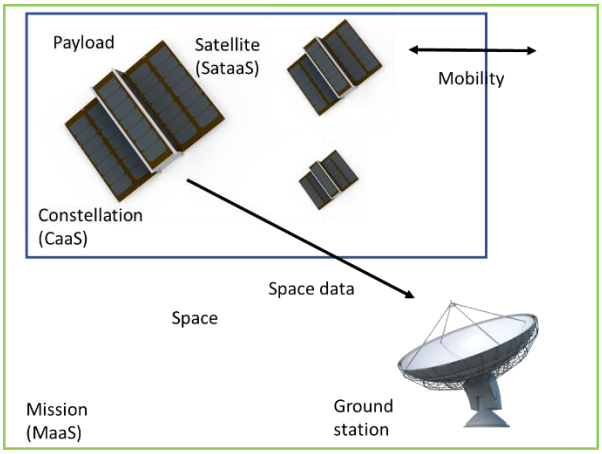

Figure 1: Overview of -as-a-Service concepts from the literature with existing abbreviations

-as-a-Service concepts related to the space segment:

- **Payload-as-a-Service**

A Payload-as-a-Service may refer to different underlying concepts. Some references interpret such a service as the payload being provided by the customer and the service provider taking care of the rest such as providing the bus, its integration into the bus, launch, operations, etc. The customer may get access to the data and may also have the possibility to operate the payload selectively [7], [8].

Other references interpret this service as the digitization of payloads, where the customer receives data but the rest is taken care of by the service provider [9]–[11]. These references are mostly linked to traditional telecommunications providers (e.g. Eutelsat) where the digitization of traditionally analogue payloads allows for unprecedented customization of service offerings. However, outside telecommunications, Spire Global has a similar offering where the service is about the delivery of data sets from Earth observation.

- **Satellite-as-a-Service**

Satellite-as-a-Service definitions from the literature can be put into at least four categories. The first shares similarities with the Payload-as-a-Service concept. The satellite is provided as a service but the payload comes from the customer [12], [13]. The second makes reference to Cloud computing, where the users "share a physical setup and various layers of the logical structure" [14] or the satellite is used as a platform for running software applications which are provided by the customer [15]. The third category comes from telecommunications network providers. From this perspective, Satellite-as-a-Service is an aggregation of services provided by individual communication satellites which can be connected to a terrestrial network more conveniently [16]. The fourth category refers to the entire satellite, including the payload provided as a service across different life cycle phases, which may include development, launch, operations, etc. [17].

- **Space Platform-as-a-Service**

Space Platform-as-a-Service [9], refers to a concept where customers can build applications on top of a space platform. This concept seems quite similar to the second Satellite-as-a-Service category, where customers can run software applications on a satellite. The enabling technologies mentioned by Spire are their network of sensors, software-defined radios and high-performance computers.

- **Constellation-as-a-Service**

Definitions for Constellation-as-a-Service follow a similar logic to Satellite-as-a-Service. Either constellations are offered as a platform on which customer sensors and instruments can be flown [18] or the constellation itself (including its sensors and instruments) is provided as a service, e.g. for collecting data from a specific geographic area [8]. Finally, the servitization of one or more life cycle phases of a constellation is also called Constellation-as-a-Service [6], [19], [20]. The last definition has some overlap with the first two definitions, as the first implies that the customer and the service provider already collaborate from the design phase onwards. For the second definition, this might be just limited to the operations phase. However, a Constellation-as-a-Service might provide capabilities beyond that by sharing a single constellation with multiple customers [21].

- **In-Space Mobility-as-a-Service**

This service is not strictly new, as space tug systems have been proposed for many decades. However, the novelty of this concept is that the customer is charged based on the propellant consumed [22], implying a pay-as-you-go scheme: "Satellite propulsion startup Benchmark Space Systems has secured customers for a new 'mobility-as-a-service' business, which similar to a taxi ride will charge them based on the amount of propellant they use." [22]

-as-a-Service concepts related to the ground segment

- **Ground station-as-a-Service**

The most well-known example of this service is the Amazon Web Service Ground Station service [23]. A key technique used by this service is virtualization by which the ground station infrastructure, including data storage, processing, and transmission via the Amazon Web Service Cloud infrastructure is hidden from the user.

-as-a-Service concepts encompassing space and ground segment:

- **Mission-as-a-Service**

Mission-as-a-Service definitions come in different flavours, similar to Payload-, Satellite-, and Constellation-as-a-Service. Exodus Orbital interprets Mission-as-a-Service as a "software-defined satellite", where a "number of different missions can be executed on this type of satellite platform, depending on the available payload instruments and subsystem capabilities. A single satellite can also host multiple instruments with sufficient capabilities to allow customers to run their software packages in parallel." [15]. Astro Digital's interpretation of Mission-as-a-Service, by contrast, emphasizes the servitization of certain life-cycle aspects such as related to design, development, and operations: "Through its Mission-as-a-Service business, Astro Digital sells satellites and related hardware along with mission planning, licensing and flight operations services." [22]

- **Space-as-a-Service**

Space-as-a-Service is usually used as an englobing term for various -as-a-Services "to denote the provision of services instead of purchases related to satellites, ground stations, and ultimately, proprietary data delivery." [24]

- **Space-Data-as-a-Service**

According to AAC Clyde Space, this service allows customers to subscribe to certain types of data sets that are delivered for a specific period of time, implying a pay-as-you-go scheme for space data [25].

From this survey, some conclusions can be drawn. First, some -as-a-Service concepts have received more attention than others in terms of the number of definitions, notable Payload-as-a-Service, Satellite-as-a-Service, Constellation-as-a-Service, and Mission-as-a-Service. Second, some of the definitions for these concepts are overlapping. For example, all concepts have at least one definition where the payload (physical and/or software) is hosted on a platform (satellite, constellation, etc.) and that platform is provided as a service (Our category: *payload hosting-oriented*). Another common type of definition is where the platform plus the payload is offered as a service (*payload plus platform-oriented*). Finally, there is at least one definition for each concept where the underlying platform and/or its instruments are shared between multiple users, using some software-based approach (*multi-user-oriented*). Table 1 provides an overview of these three types of definitions, common to these -as-a-Service concepts.

Note that the multi-user-oriented category may come with some form of virtualized or digitized payload, where the actual payload is hidden from the customer. In this case, there is an overlap with the payload plus platform-oriented category. However, Loft Orbital's service offering may also fall into the payload hosting-oriented category, as multiple payloads are hosted but customers can operate them independently. Hence, the distinction depends on the use of the underlying technology such as virtualization.

Table 1: Different types of definitions of -as-a-Service concepts for the space segment

Service Type	*Payload hosting-oriented*	*Payload plus platform-oriented*	*Multi-user-oriented*
Customer role	Provides payload	Receives results, usually data, may operate via interface (does not provide payload)	Provides payload and/or receives results, usually data, may operate via interface
Service provider role	Operates payload	Takes care of entire life-cycle	Takes care of entire life-cycle

3. A Taxonomy of New Space Services

We borrow a framework from the domain of product-service systems and apply it to new space services. The

main reason for borrowing an existing framework is that abundant literature on services already exists such as in service design [26], service engineering [27], and product-service systems [28]. While service design and service engineering focus on services, the product-service systems literature emphasizes transitioning from a product-centric to a service-centric view (servitization) and seems pertinent to the case of new space services.

The product-service systems (PSS) literature provides a conceptual basis for understanding (so-far) terrestrial bundles of products and services. PSS have emerged in many terrestrial applications, where companies transform their business model from a product-centric one (selling cars, jet engines) to a service-centric one (mobility service, renting jet engine hours). Numerous definitions for PSS have been proposed [2], [29]–[33]. Most definitions consider PSS as either a business model / innovation strategy or as a combination of product(s) and service(s), depending on the emphasis on the business impact of PSS or its embodiment in the form of products and services [34].

As our survey of -as-a-Service concepts has shown, they seem to reflect this dual nature of PSS. -as-a-Services can be understood as a business model (e.g. selling data instead of a satellite) and/or the underlying product(s) (e.g. satellite and payload) and service(s) (e.g. providing satellite data). Hence, it seems that the concept of PSS is pertinent to -as-a-Service concepts.

Regarding PSS taxonomies, Tukker [2] has introduced the most widely cited one and we will use it in the following for categorizing the -as-a-Services. Tukker looks at the degree a PSS relies on the product or service element. He introduces three categories, as shown in the top row of Table 2. A *product-oriented PSS* is a product with some add-on services such as after-sale services for a car, e.g. maintenance. *Use-oriented PSS* are PSS where, for example, multiple users are using / leasing a product such as a car. It is easy to see how this PSS category applies to several -as-a-Services. *Result-oriented PSS* emphasizes results instead of how the results have been achieved. For example, pay-as-you-go services would fall under this category. Many traditional space services such as telecommunications or buying images from Earth observation would also fall under this category.

It is no surprise that no -as-a-Service type falls under the product-oriented category, as the notion of "-as-a-Service" implies that a previously product-based business model was transformed into a service-based one. We also observe that most -as-a-Service types fall under the use-oriented PSS category, some under the result-oriented category. An explanation is that most -as-a-Service types are an effort to transition from a traditional product-centric paradigm to a service paradigm and the X in X-as-a-Service indicates what product has been transformed into a service (payload, satellite, etc.).

Table 2: -as-a-Service types mapped to PSS categories according to Tukker [2]

PSS category	**Product-oriented**	**Use-oriented**	**Result-oriented**
-as-a-Service types falling under PSS category		Payload Satellite Spacecraft Constellation Infrastructure Ground station	Mission Space data Mobility Payload Satellite Spacecraft Constellation

Instead, many traditional space services such as navigation, telecommunications, and Earth observation have already been result-oriented business models. However, the reason why Payload-, Satellite-, Spacecraft-, and Constellation-as-a-Service appear in both columns is that depending on which type of definition is used, harkening back to Table 1, the service can also be result-oriented without a particular reference to how it has been provided.

Note that Tukker remains technology agnostic making the taxonomy orthogonal to the one for certain space segment -as-a-Services provided in Table 1.

4. A Framework of New Space Services

In the following, we will go into further depth in our analysis of -as-a-Services by using elements of a modelling language previously developed by Hein et al. [35], building on the results presented in Table 1. We use the example of Satellite-as-a-Service to look at the question of the boundary between customer and service provider, using three exemplary definitions. While Tukker [2] considers this boundary, a more in-depth treatment, in general, is given in the service design literature, in particular in Service Blueprinting [26], [36].

Figure 2 shows three models for Satellite-as-a-Service based on three definitions from the literature. It can be seen from the model for the Exodus Orbitals definition [15] of Satellite-as-a-Service that ownership and operations of the satellite are with the service provider as well as offering the service of hosting (software) applications on the spacecraft. The customer (application provider) owns and potentially operates its application on the spacecraft. This definition of Satellite-as-a-Service has a strong resemblance to the concept behind the ESA OPS-SAT mission, where applications are hosted on a spacecraft [3].

The Eutelsat definition [16] of Satellite-as-a-Service has its origin in telecommunication networks. While its structure seems similar to Exodus Orbitals' its content is different, i.e. the service provider provides a space network service and owns and operates the underlying satellites. The terrestrial network operator owns and operates a terrestrial network which receives the space network services.

The Ellipsis Drive definition [17] leaves room for interpretation, as it is a priori undefined which satellite life cycle phases are servitized. In the extreme case where all phases are servitized, the satellite user would only receive data from the satellite via a user interface, while the service provider takes care of all other aspects of the satellite. This definition of Satellite-of-a-Service goes far beyond the Exodus Orbitals definition, as in the latter, the customer still provides some payload element to the satellite (the application). Instead, in the extreme case of the Ellipsis Drive definition, the satellite user no longer provides hard- and/or software for the satellite.

From these three definitions, we can see that the first two share structural commonalities, which are common to use-oriented PSS, namely, a service provider who owns and operates a product (here, satellite(s)) and some customer-owned product interacts with it (application, terrestrial network). This may hint at a recurring pattern, as payload hosting services, Constellation-as-a-Service, etc. may follow a similar logic where some products developed by customers (payload, sensors, software, etc.) are interacting (hosted, operated, etc.) with the service provider. The Ellipsis Drive definition in its extreme case creates a transition to Mission-as-a-Service, if the latter is interpreted as "The service provider takes care of the entire mission and the customer gets the results."

At a more general level, what crystallizes from this example is that there are two different perspectives on how to set the boundary between the service provider and the customer. The first is at the technical level, where the interface to the customer is set. This is sometimes called line of interaction (e.g. technical interfaces) and line of visibility (what the customer can "see", e.g. specifications of host spacecraft with which the customer does not interact) in service design, e.g. Service Blueprinting [36]. We focus on the line of interaction in the following and consider it as our main boundary. Traditionally, customers in a satellite mission would be responsible for the payload and interact via the payload interface with the spacecraft bus provider. This is still the case for payload hosting. However, this interface might be shifted in front of the payload, where the interface is no longer between the payload and the bus but the data interface of the spacecraft.

Nevertheless, subtle differences exist: While a completely result-oriented data interface is possible, e.g. such as for traditional telecommunications, navigation services, some companies (e.g. Spire Global, Loft Orbital) offer the possibility to rent or operate a sensor suite for a given period of time, which means that this interface goes beyond a pure down- or uplink to the spacecraft but an interface which allows for access to a payload, which can be achieved by a virtualization of the spacecraft, similar to a virtual server for a customer of the Cloud, which is abstracted away from the underlying Cloud infrastructure.

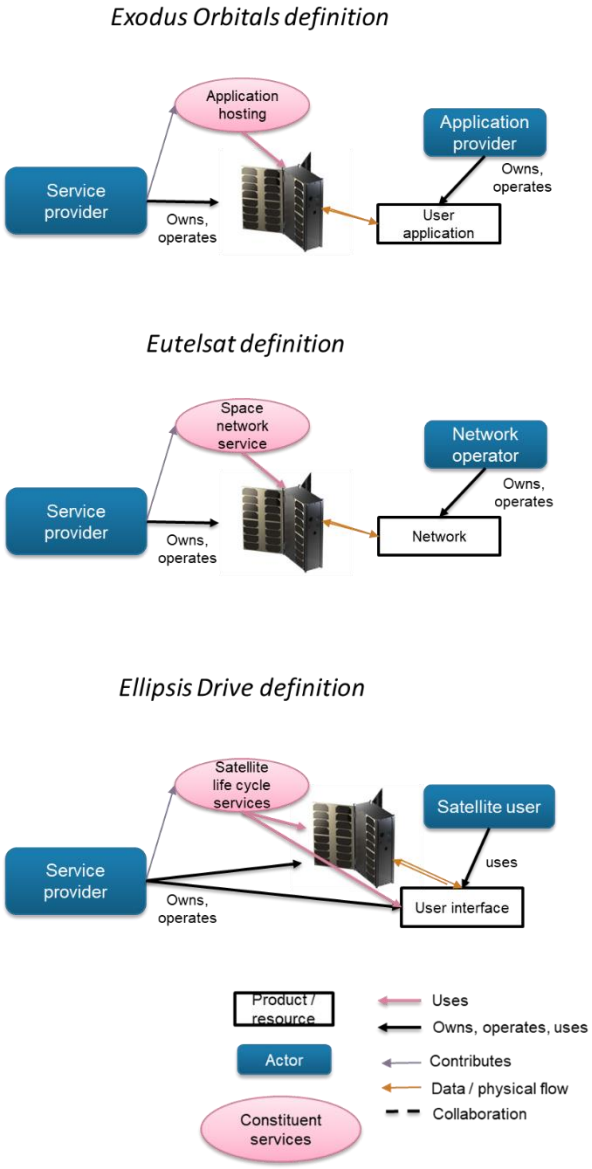

Figure 2: Simplified models of some Satellite-as-a-Service definitions

What automatically comes into play here is the second perspective on where to set the boundary: the lifecycle phases. While payload hosting has many elements in common with traditional space missions, Constellation-as-a-Service in the sense of renting / using a set of sensors for a given period of time and acquiring

data is new. In this case, the interface between the customer and the service provider is a priori limited to the operations phase. In the case of Satellite-as-a-Service, the interface might be set at different steps of the life cycle and might span the entire life cycle. Figure 3 illustrates these two dimensions of setting the boundary, where the dashed lines visually illustrate how they can be moved to bound areas which are under the responsibility of the service provider and those areas external are provided by the customer. The alternatives on both dimensions create a combinatorial set of alternative designs of -as-a-Services.

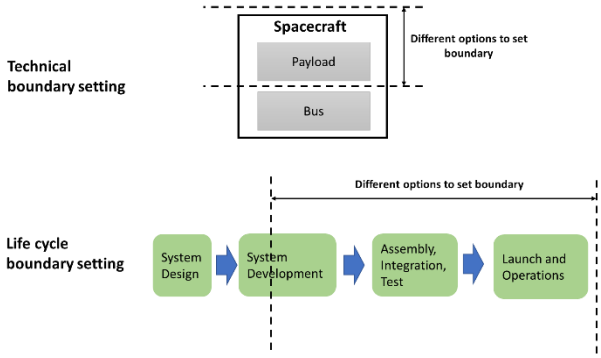

Figure 3: Alternatives for setting the boundary (lin of interaction) in a -as-a-Service

5. Discussion

From looking at different definitions of -as-a-Service types, we can conclude that those definitions are different but the difference mostly originates from the context in which they have emerged, e.g. legacy telecommunications network provider vs. new space company. The differences also stem from analogies and references to terrestrial Cloud computing, in particular Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), and Software-as-a-Service (SaaS). This is particularly interesting, as such an explicit reference is missing in the PSS and service design literature. The obvious reason for that reference is that the -as-a-Service notion was coined in the context of Cloud computing with SaaS as the most prominent one. However, the reference goes beyond adopting the suffix.

New space services borrow several elements from Cloud computing. First, the boundary between what the customer provides and the service provider provides is similar, as has already been mentioned for IaaS (customer provides application, operating system, middle-ware etc.; Service provider provides infrastructure), PaaS (Customer provides application; Service provider provides the operating system, middle-ware, etc. and infrastructure), SaaS (customer uses application; Service provider takes care of the application, all other layers, and infrastructure). Second, the principle of virtualization is adopted, where the physical infrastructure is abstracted away via a virtualization layer. This is a key approach in Cloud computing where the physical server infrastructure is hidden from the user. Virtualization has the advantage to let multiple users the same infrastructure without the need for physical compartmentalization. For example, multiple missions can be run on the same physical spacecraft by establishing a "virtual" spacecraft that is specific to each customer and may include a set of "virtual" instruments. Constellations-as-a-Service could be "virtualized" by assigning "virtual" constellations to specific customers.

An important question is how far new space services are different from traditional space services such as navigation, telecommunication, and Earth observation. The main differences are summarized in Table 3. Most new space services are based on a shift from a product-oriented business model to a use-oriented business model, in some cases a result-oriented business model. Instead, traditional space services are commonly result-oriented.

Table 3: Differences between traditional and new space services

Aspect	Traditional space service	New space service
Business model	Result-oriented	Shift from traditionally product-oriented business model to a use-oriented business model, in some cases a result-oriented business model.
Reference / legacy	Analogous terrestrial services	Cloud computing: IaaS, PaaS, SaaS, virtualization
Life cycle phases concerned	Operations	Servitization of some to potentially all life cycle phases.

New space services commonly refer to Cloud computing, including its service types (IaaS, PaaS, SaaS) and the underlying technology such as virtualization. Traditional space services mostly have a long track record and have referred to various paradigms of their respective field, e.g. broadband, 5G, etc. for telecommunications. However, rather than porting a certain concept to space such as broadband telecommunications in space, new space services adapt certain principles or underlying technologies to space. While the link to Cloud computing is strong, new space services go beyond a pure adoption of Cloud computing

to the space context. Rather, it takes it as an analogy or an underlying technology for proposing new types of services. For example, Satellite-as-a-Service has a similar underlying technology and principles as Software-as-a-Service but the underlying infrastructure is a spacecraft with a combination of sensors, actuators, etc. which is different from a computational infrastructure such as the Cloud. The closest terrestrial analogy might be a Cloud-based system for robotics (Cloud robotics) where a combined computing and robotics infrastructure provides services [37].

As traditional space services are commonly result-oriented, their interaction with the user is during the operations phase. In contrast, new space services may span a variety of life cycle phases, including design, development, and disposal. Examples are offerings (e.g. NanoAvionics) to accompany customers with their payload throughout all life cycle phases.

The potential advantages of new space services might be similar to the ones of associated with Cloud computing on Earth:

- A reduction of the entry barrier of developing applications for a given domain, due to moving from CapEx to OpEx, similar to terrestrial e-commerce (running prototypes immediately on the Cloud to gain traction instead of investing in infrastructure first).
- Quick, on-demand scalability of application if the space infrastructure provides sufficient capacity by the service provider.
- No long-term commitment to a specific infrastructure for the customer and the option to switch between offers, although lock-in is possible if standardization is low, e.g. interfaces for payload hosting.
- Flexibility in addressing changing customer needs.
- Economy of scale and learning effects due to leveraging commonalities in customer needs and equipment procurement.

How far these benefits materialize remains to be seen. However, looking into the future, we might see space companies following strategies similar to their terrestrial analogues, for example, to invest in large infrastructures to create economy of scale effects and a significant price advantage. This might further reduce the entry barrier to develop space applications and might lead to a surge of new space start-ups, analogous to the Cloud, enabling a surge of e-commerce start-ups, which are capable of rapidly scaling their ventures.

Such a development may also open the path towards complex, collaborative new space services, where individual services are combined to form a higher-level service. Individual services may deal with specific types of computing, data storage and processing, sensors, and actuators, allocated to various space systems. Such complex collaborative services may lead to unprecedented capabilities and new business models in space.

6. Conclusions

This paper provided an initial survey of various new space service concepts in the space domain with a focus on "-as-a-Service" services and presented a taxonomy and framework for these emerging services. New space services, contrary to traditional space services have their origin in a transition from a product- to a use-oriented business model and a reference to Cloud computing. Analogous to the terrestrial impact of Cloud computing on the emergence of numerous e-commerce start-ups, we might see a similar surge of in-space applications, building on a new space service backbone. Such a development is likely going to be enabled by the shift from traditionally high capital expenditures of developing space applications to operating expenses, thereby lowering the entry barrier.

For future work, we aim to further refine our taxonomy and framework to move towards tailored design methods for new space services. A particular emphasis will be the currently overlooked link between new space services and potential sustainability benefits such as the reduction of space debris via a lower number of launched spacecraft (e.g. multiple payloads hosted on single spacecraft instead of each payload on a separate spacecraft).

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