

Review

A Systematic Review of Product Design for Space Instrument Innovation, Reliability, and Manufacturing

Kai-Leung Yung¹, Yuk-Ming Tang^{1,2,*} , Wai-Hung Ip^{1,3} and Wei-Ting Kuo^{1,2}

¹ Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong; kl.yung@polyu.edu.hk (K.-L.Y.); wh.ip@polyu.edu.hk (W.-H.I.); david.kuo@polyu.edu.hk (W.-T.K.)

² Laboratory for Artificial Intelligence in Design, Hong Kong Science Park, New Territories, Hong Kong

³ College of Engineering, University of Saskatchewan, Saskatoon, SK S7N 5A2, Canada

* Correspondence: yukming.tang@polyu.edu.hk

Abstract: The design and development of space instruments are considered to be distinct from that of other products. It is because the key considerations are vastly different from those that govern the use of products on planet earth. The service life of a space instrument, its use in extreme space environments, size, weight, cost, and the complexity of maintenance must all be considered. As a result, more innovative ideas and resource support are required to assist mankind in space exploration. This article reviews the impact of product design and innovation on the development of space instruments. Using a systematic literature search review and classification, we have identified over 129 papers and finally selected 48 major articles dealing with space instrument product innovation design. According to the studies, it is revealed that product design and functional performance is the main research focuses on the studied articles. The studies also highlighted various factors that affect space instrument manufacturing or fabrication, and that innovativeness is also the key in the design of space instruments. Lastly, the product design is important to affect the reliability of the space instrument. This review study provides important information and key considerations for the development of smart manufacturing technologies for space instruments in the future.

Keywords: space environment; space instrument; product design; performance; innovation; manufacturing



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1. Introduction

Gold et al. [1] stated that space instruments are essential components for most space missions. The instruments help in gathering intelligence information, observing other planets, and monitoring the environment on earth. Providing the data to analysts and scientists on the ground, instruments are important for spacecraft in conducting regular structural verification (Garcia, [2]). During the launch operation of space missions, a mechanical environment that combines high and low frequencies, shock loads and vibrations, and high static acceleration, is generated. Each type of mechanical load must be simulated by analysis and tested to qualify the mechanical design. Some examples of space instruments include the supra thermal electrons and protons (STEP) instrument, which is constituted with other instruments such as the supra thermal ion spectrograph (SIS) and the energy particle detector (EPD) for solar orbiter spacecraft. Innovation, reliability, and product design [1] are essential for scientists to miniaturize space instruments. The size of the launch vehicle can reduce the weight of the instruments, allow the transition to smaller launch vehicles and provide accurate measurements from the space. Scientists have also modified the product designs of space instruments by creating completely new space instruments that enable previously impossible measurements. For instance, hyperspectral observations of the settings below the horizon and stars by visible imagers, spectrographic imagers, and ultraviolet imagers on the Midcourse Space Experiment Spacecraft. Tam [3]

states that the best way to improve space instruments is by improving the technology through innovation, which may be in the form of designing space instruments with fewer components. Chau et al. [4] investigated the critical success factors (CSFs) for improving the management in manufacturing. Instead of using the traditional manufacturing method of using nuts and bolts to join complex systems and subsystems, new technologies such as Industry 4.0, 3D printing, and additive manufacturing could be used to produce complex yet monolithic structures, which do not require nuts and bolts. The process of innovation will help in reducing the number of pieces that might break down in case of a collision in orbit. Recently, a new method to design using “replicative” structures in different sizes and achieve required mechanical properties to manufacture with the minimum weight is investigated in [5]. In the study, manufacturing process parameters and design performance are analyzed with various examples.

Nevertheless, most of the smart manufacturing processes are mainly applied to traditional product development. Not many works are focused on developing smart manufacturing for space instruments and devices. This is because the space instrument usually consists of numerous factors such as size, weight, cost, extreme space environmental conditions, as well as a large number of components, high reliability, and stability, etc. With the recent advancement of Industry 4.0 and smart manufacturing technologies such as artificial intelligence, big data, augmented reality [6], and blockchain, it is important to extensively explore the product innovation, design, and reliability issues and CSFs in order to develop an optimal solution of smart manufacturing for space instrument. The main aim of the study is to explore how innovation and product design is essential in the development of space instruments and manufacturing. The study addresses the following key research questions.

RQ1: The research focuses on the development of space instruments;

RQ2: The key consideration factors that may influence the design of the space instrument.

This article presents the key contributions in the field. First, there is not much research focus on the design and development of a complex space instrument. Second, this study explores the influences of product innovation and design on the development of space instruments that are important to formulate the key consideration factors in the design and manufacturing of a complex space instrument. The key factors are important in formulating the smart manufacturing protocol for space instruments in the future. This is important to enhance the design and manufacturing efficiency of space products in the field.

2. Literature Review

2.1. Space Instrument

To design a space instrument or spacecraft to work in the space environment, three issues are important, making the design process very difficult, challenging, and exciting. The first one is that the complicated instrument work in a tough environment. This required high precision on the material selection and the physical mechanism. Moreover, the design and manufacture must have high precision to achieve the requirements for the best quality. Second, as the instruments will work remotely from the Earth, signal communication between the earth center and the instrument is a big concern. On the other hand, the design for the processes command, self-calibrate and operation are the other remotely issue. The third is the sensor. As there are many unknown environments in space, the sensor is the only reliable and detectable component for us to understand the situation. However, regarding the unknown environment, investing in a sensor to complete the mission is a big challenge. These issues are important in many processes of a space mission instrument such as space component replenishment. Yung et al. [7] proposed the multi-attribute fuzzy ABC classification to support the space components inventory decisions based on the tough situation of space missions.

All early and most current space programs are carried out or strongly dominated by governmental programs and choices. The reason for those monopolies is related to the high technical skill and knowledge required for developing space instruments and it

is not worth it for a business to step into the industry. However, along with the mature environment of technology and the large developing margin in the deep space environment, such as mining, space travel, etc., more and more businesses are interested to enter the space market. The most outstanding example is the SpaceX program, developed by Elon Musk, the owner of the Tesla Company.

2.2. Product Development Process

2.2.1. Product Innovation

The exploitation and exploration of space have led to the emergence of new technologies in science including areas such as telecommunications, navigations, and medicine (van der Veen et al. [8]). Product innovation is the major goal of the space fairing nations to increase the capabilities of space technology to increase the benefits of space utilization. Over the generations, the space sector has focused mainly on advancing the technology conservatively, as well as innovation increments that are of low risks instead of disruptive, radical, and breakthrough innovations.

According to Popa et al. [9], the concept of innovation presents the ability to continuously make ideas and knowledge into new systems, processes, and products. Innovation can be divided into three pairs, radical innovation-incremental innovation, process innovation-product innovation, and technical innovation-administrative innovation. Incremental innovation refers to improving the existing processes, services, and products, radical innovation refers to the re-conceptualization of the products and process, and process innovation refers to the introduction of new elements to various processes. Administrative innovations refer to innovations that are related to the basic activities of the administrative processes as well as the management of those processes, and technical innovations refer to the products and technology innovations in the production process such as using Blockchain technology to enhance the traceability and trackability of the aerospace and aviation industries (Ho et al., [10]).

Van der Veen et al. [8] described disruptive technology as the kind of technology that emerges out of the niche market and dominates the market to the extent of disrupting the status quo of the market. Innovation is described as disruptive when it starts to appeal to the majority of users of the technology in the market. The technological capabilities of the space sector are steadily increasing due to the development and research efforts and the resulting space innovations. Tkatchova [11], however, indicated that innovation in space is different from other technological innovations due to the harsh environment experienced in space. The space environment makes it hard for space instruments to operate. According to the authors, the operating environment in space is determined by factors such as the microgravity environment, the high g-forces during the launch of the instruments, the vacuum environment, the temperature variations, extreme temperatures, and high-energy radiation. It is argued that space technologies are highly subject to the performance of the customer, which is similar to non-space technologies. The disruptive space technology differs from the other types of technologies in various ways: long development time with a high response time for new disruptive technologies, flight heritage, and market characteristics.

2.2.2. Disruptive Technologies in the Space Industry

Disruptive space technology is therefore a technology that changes the status of the space sector radically by having an alternative perceived performance mix, which fulfills the technical requirements of the user better than the previous technology (Van der Veen et al. [6]). The key difference between disruptive space technology and other space technologies is the fact that disruptive space technologies gain their relevance by outperforming the alternative performance mix that is valued by the customers of the niche market. In the space sector, there are various kinds of innovations to achieve the outperforming value.

A space elevator is an example of a disruptive innovation that has taken place in the space sector in the past years. According to Courtland [12], space elevators were proposed as a cheap alternative to costly rockets. The air elevator was considered a cheap alternative to transport cargo and humans into space.

The space elevator was designed to be made of a cable that was to be anchored to the surface of the earth and balanced by a counterweight in the space. On earth, the cable would have lasers that would beam power the climbers. The climbers would then crawl up the cable with their cargo to space. The technology has however stuck on the ground for years without progress. One of the main reasons the disruptive technology has not taken place is because the current materials are not strong enough to support the strain on the cable. Through carbon nanotubes have been found, it would be great news for the space elevators. Even with adequate materials, the concept of space elevators is still not achievable as it will still be highly unstable. This is because of the gravitational force from both the sun and moon as well as the pressure resulting from the solar wind. The solar wind and gravitational force would shake the cable causing the elevator to crash with other satellites. The author however recommends that thrusters are needed to keep the cable in line. Some of the significant negative effects expected to be caused by space elevators include sending a spacecraft to the wrong orbit, resulting in a slow crawl as compared to rocket launchers.

The motion of the cargo in the elevator will cause the cable to shake, which will either reduce or boost the velocity of the spacecraft exiting the elevator. The wobble could then send the spacecraft to the wrong orbit as well as damaging the elevator. The climbers in the space elevator also have to climb low to avoid creating large effects on the cable. Though slowing down the climbers can help minimize the effect, it will also slow down the trips to space. Ander Jorgensen of the New Mexico Institute of Mining and Technology indicated that building space elevators seem to be more complicated than originally expected.

2.2.3. Product Design

Product design is a situation or activity where people take industrial products as the main object for development and survival (Ren, [13]). The key to successful product design is an understanding of the end-user customer, the person for whom the product is being created. Khadke [14] stated that it is essential to consider the importance of technology innovation in product designs to avoid the destruction of key components as well as frequent redesign costs. Product designers attempt to solve real problems for real people by using both empathy and knowledge of their prospective customers' habits, behaviours, frustrations, needs, and wants.

Other than product design in normal practice, the product design process is much more complicated for space instruments. One of the reasons is the tough environments that the instrument needs to face. Another reason is the high accuracy of the product. There are a lot of trial-and-error processes during the product design stage. Moreover, there are many concerns not considered in earth products that are required to be included in the space instrument design. According to Meller [15], the product design for space instruments must have a low mass as well as high strength because of the hostility they face in the space environment. The product design used for creating the instruments should be able to avoid metal-to-metal contacts, must use liquid lubricants that are vacuum compatible as well as giving hardware error correction. In manufacturing space instruments, the manufacturers also have to incorporate latch-up protection circuits into the product design as well as radiative heat transfer mechanisms.

2.2.4. Reliability

The reliability of a space instrument is its ability to provide consistency in space and time or from different observers (Souza et al. [16]). According to the authors, reliability is one of the main quality criteria of an instrument regarding its ability to present aspects on homogeneity, equivalence, stability, and coherence. It refers to the equivalence, internal

consistency, and stability of the space instrument. In space instruments, have the responsibility of ensuring the instruments are reliable for use in space. They should ensure that the onboard computers for the satellites are reliable as well as the infrastructure required for operating the instruments from the ground. According to the European Space Agency, there are no second chances in space missions hence reliability is a crucial aspect of space instruments. The current trend of increased autonomy of space systems and the unpredictable and rapid rate of technology change also poses new challenges to the reliability of the instruments. Reliability is therefore one of the main quality criteria of an instrument regarding its ability to present homogeneity, equivalence, stability, and coherence.

3. Methodology

3.1. Research Design

The study explores the relationships of innovation, product design, and reliability of space instruments. To do this, we conducted a review of previously published studies regarding space instruments and then analyzed the articles to investigate their findings. We systematically evaluate previous studies performed by different people to derive a conclusion about the research being carried out (Haidich [17]). The outcomes of analysis include a more precise estimate of the research body than any separate study, thus contributing to the collective analysis. The systematic review was carried out using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analysis). According to Labaree [18], the PRISMA is designed to systematically summarize and evaluate the results from previous studies that meet the selection criteria of the research paper.

The selection of studies to be used is the first step in systematic analysis. According to Meline [19], the process involves the search of multiple databases to locate all studies that are potentially useful to determine the answers to the research questions. Secondary literature and data were used in the analysis. Secondary literature was composed of explanations and assessments from the primary result literature. The primary literature can be obtained, generalized, and summed up by researchers who can, later, generate new research. The studies used for the research originated from various databases that contained research papers related to the research topic. The research investigated papers that were published in English and incorporated search terms such as qualitative research and other terms related to the research topic. The Web of Science (WoS) database was used for investigation in this study. It is because the WoS is one of the widely used databases for research articles in academic disciplines. It also enables access to multiple databases that provide comprehensive citation data. We applied the following keywords in this study and select the articles until the end of September of 2021: “instrument” AND “space environment” AND “design”.

This study mainly considers space instruments, the design of space instruments, and the space environment. However, the research does not indicate a specific timeline for the studies because we wish to acquire all the studies that had relevant information irrespective of the year it is published in order to explore the evolution of the design and manufacturing of space instruments.

3.2. Exclusion and Inclusion Criteria

The eligibility criteria specify the studies that will be included and those that will be excluded from the review (Meline [19]). The studies were selected and evaluated for eligibility based on their acceptability and relevance. The inclusion and exclusion criteria were guided by two questions: whether the study was acceptable for the analysis and whether the research was relevant to the purpose of the analysis. The full texts of the studies examined during the research were used to determine the study’s trustworthiness and reliability. This study considered articles that were peer-reviewed and were written in the English language. After searching the terms based on the pre-defined keywords, the articles were later screened. The articles selected were those that met the inclusion criteria were retained within the study (Table 1).

Table 1. Inclusion and exclusion criteria.

Inclusion	Exclusion
Studies discussed space instruments and other topics relating to space exploration	Studies that did not discuss space instruments and other topics relating to space exploration
Studies that researched the space environment and the current trends in space exploration	Studies that failed to research the space environment and the current trends in space exploration
Journal articles that focus on the product designs or manufacturing of the space instruments	Journal articles that did not focus on the product designs or manufacturing of the space instruments
Journal articles published in the English language	Articles not published in the English language
Peer-reviewed articles	Articles that were not peer-reviewed

3.3. Sources of Information and Relevant Studies

This review followed the four-stage stream chart of PRISMA in looking for the investigations pertinent for the examination. PRISMA was utilized as it empowers to locate a wide scope of investigations of premium and suitable examinations for the exploration question (Moher et al. [20]). The four stages of PRISMA are recognizable proof, screening, qualification, and consideration of studies. The study used a single WoS database to search for relevant papers. The databases were utilized as they were considered to have increasingly centered data around the sort of studies and the researcher was searching for.

4. Results

To address the research questions of this study, the results are divided into several sections. The first section is to address the first research question on investigating the research focuses of the existing studies. Then, the research questions on the key consideration factors that may influence the design of the space instrument are discussed next. Further elaboration on the reviewed studies and the key consideration factors are elaborated in Sections 4.3 and 4.4, followed by the review on the product design and reliability.

4.1. Research Focuses

Figure 1 illustrates the overall systematic review process and the number of searched articles based on PRISMA. After searching the databases, 129 records were found. After removal of the similar and screening of the articles', and screened based on the inclusion and exclusion criteria, there were only 56 studies were left. Out of the 56 studies, 8 were excluded as the articles are not related to the instrument or product design nor manufacturing. After running through the inclusion and exclusion criteria and screening processes, only 48 remained for the final review. Any disagreement regarding the selection of the studies was resolved by keeping the research objectives as the focus. A systematic analysis was then conducted on the selected articles to extract information about the topic of the studies, the sample sizes, and the findings of the studies. Table 2 illustrates the summary of the research focuses of the articles on innovation, product design, instrument performance, and manufacturing. The articles were sort according to the last name of the first author. The instrument used in each study were also illustrated. It was found that most of the space instruments were applied in various outer space environments including orbit, spacecraft or space station, satellite or space telescope, lunar, mars, and mercury planetary missions, etc. Most of the research articles were focused on product design and instrument performance. It was also found that many of the product innovations were associated with the instrument product design, followed by the instrument fabrication and manufacturing of technologies. Innovation referred to the adoption of novel technologies and ideas, improvement of existing instruments using new techniques. In which, most of the instrument performance research focuses were related to the product design.

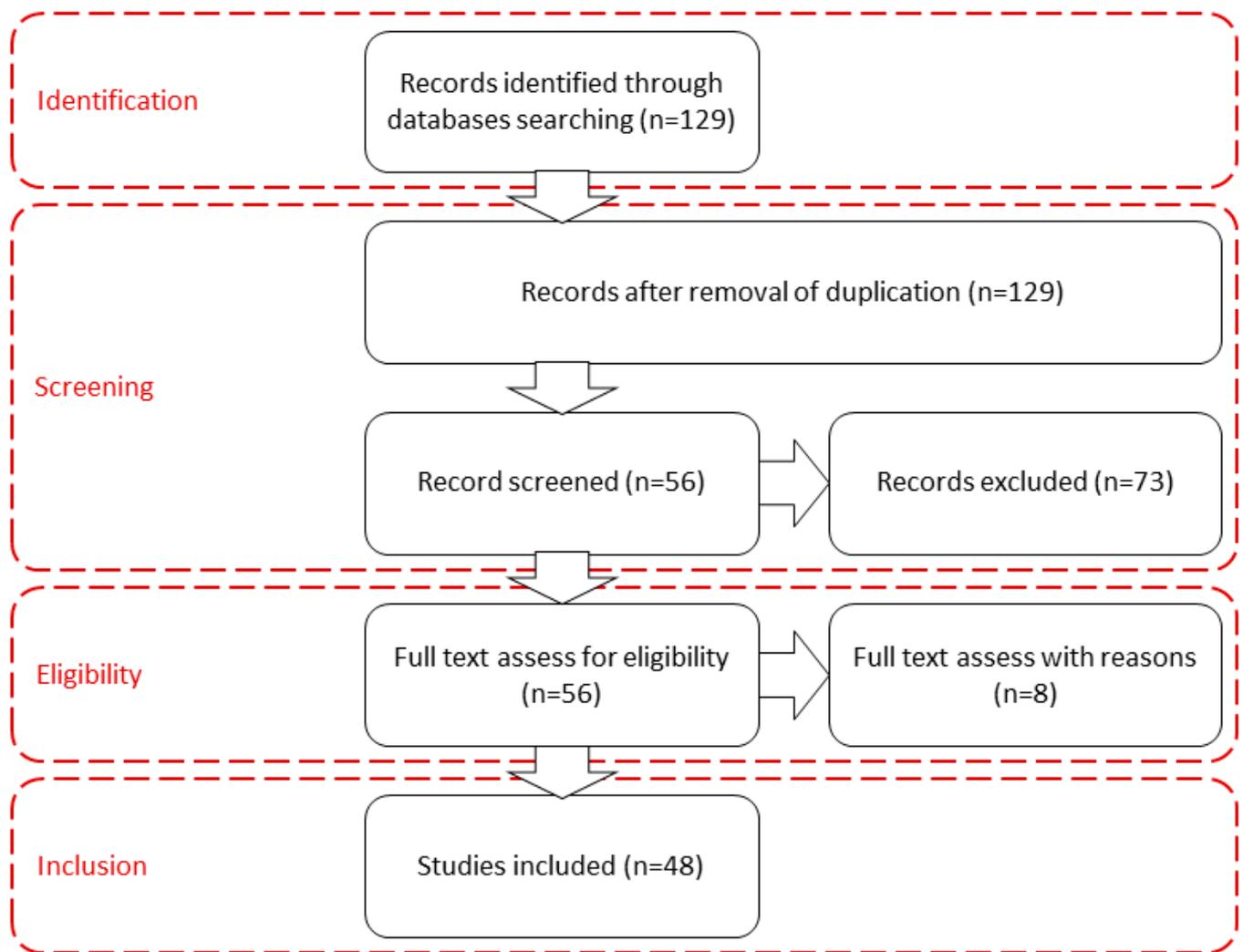


Figure 1. Systematic review on the instrument design of the space industry.

Table 2. Summary of the studies information and their research focus on innovation, product design, instrument performance, and manufacturing.

Authors	Year	Ref.	Instrument	Environment	Research Focus			
					Performance	Product Design	Innovation	Manufacturing
Barker	2018	[21]	Thermal Infrared	Lunar, Mercury		✓		✓
Biasotti	2020	[22]	Lunar Orbiter Laser Altimeter	Lunar	✓	✓		✓
Borgarelli	1998	[23]	Cassini Radar	Spacecraft		✓		
Bunce	2020	[24]	Imaging X-ray Spectrometer	Orbit	✓	✓		
Cavanaugh	2007	[25]	Mercury Laser Altimeter	Mercury	✓	✓		
Clark	2016	[26]	Energetic Charged Particle Detectors	Space		✓	✓	✓
Cress	2020	[27]	Falcon Solid-State Energetic Electron Detector	Orbit	✓	✓		
Delkowski	2021	[28]	Optical and Radar Instrument	Space			✓	✓

Table 2. Cont.

Authors	Year	Ref.	Instrument	Environment	Research Focus			
					Performance	Product Design	Innovation	Manufacturing
Dichter	1998	[29]	Compact Environmental Anomaly Sensor	Spacecraft		✓		
Dichter	2015	[30]	Gene Expression Measurement Module	Space	✓	✓	✓	
Dickie	2017	[31]	Micromachined Plasma Spectrometer	Satellites	✓	✓		✓
Dou	2017	[32]	Proton Microprobe	Space		✓		
Gilbert	2010	[33]	X-rays Space Telescopes	Space Telescope		✓		✓
Godet	2009	[34]	X- and Gamma-Ray Sensor	Space	✓			
Goldsten	2007	[35]	Gamma-Ray and Neutron Spectrometer	Spacecraft		✓		
Hall	2017	[36]	Charge-Coupled Device	Space	✓	✓		
Han	2016	[37]	Differential Electrostatic Space Accelerometer			✓	✓	✓
Hsiao	2010	[38]	Radiatively Cooled Instrument	Space	✓	✓		
Hu	2014	[39]	Scanning Fabry-Perot Interferometer	Space Station		✓		
Hudson	2007	[40]	Differential Electrostatic Accelerometer	Orbit	✓	✓		
Koehn	2002	[41]	Fast Imaging Plasma Spectrometer	Mercury		✓	✓	
Koga	3002	[42]	Neutron Monitor	Space Station		✓	✓	
Krebs	2005	[43]	Mercury Laser Altimeter	Mercury		✓		
Lepri	2017	[44]	Fast Imaging Plasma Spectrometer	Mercury		✓		
LIFE	2019	[45]	Charged Particle Instruments	Orbit	✓	✓	✓	
Lindstrom	2018	[46]	Environmental Anomaly Sensor	Space		✓		
Ling	2019	[47]	Space Welding Technology	Space			✓	✓
Liu	2021	[48]	Mass Spectrometers	Space			✓	
Lopes	2021	[49]	Radiometers	Space	✓	✓		
MacDonald	2006	[50]	Magnetospheric Plasma Analyzer	Satellites		✓		
Magnes	2020	[51]	Space Weather Magnetometer	Orbit		✓		
Mauk	2017	[52]	Energetic Particle Detector Instruments	Jupiter	✓	✓		
Moretti	2010	[53]	Magneto-Optical Filter-based system	Space	✓			
Ostgaard	2019	[54]	X- and Gamma-Ray Sensor	Space Station	✓	✓		

Table 2. Cont.

Authors	Year	Ref.	Instrument	Environment	Research Focus			
					Performance	Product Design	Innovation	Manufacturing
Rothkaehl	2011	[55]	Plasma-Wave Complex	Space Station	✓	✓		
Sadrozinski	2002	[56]	Gamma-ray Large Area Space Telescope	Space		✓		
Schlemm	2007	[57]	X-ray Spectrometer	Mercury		✓		
Soli	1995	[58]	Proton-spectrometer	Spacecraft, Satellite		✓		
Swinyard	2000	[59]	Moderate-Resolution Imaging Spectroradiometer (MODIS) Instrument	Orbit	✓	✓		
Thuillier	1992	[60]	Michelson Interferometer	Satellites	✓	✓		
Warren	2017	[61]	Differential Electrostatic Space Accelerometer	Space Station		✓		✓
Wei	2013	[62]	X-ray Detector and Energetic Particle Detectors	Space			✓	
Wesolek	2005	[63]	Microwave Sounder Instrument	Space		✓	✓	✓
Wise	1995	[64]	Materials in Devices as Superconductors	Spaceflight	✓	✓		✓
Wright	2013	[65]	Thermal Hyperspectral Imager	Space		✓		
Xiong	2019	[66]	Optical Thin Films	Space		✓		✓
Zanoni	2016	[67]	Doped Germanium Photoconducting Detectors	Space	✓			
Zurbuchen	2016	[68]	Plasma sensors	Space			✓	

4.2. Key Consideration Factors on Instrument Design

The results of the studies are summarized in Table 3. The summaries for the selected papers are given in terms of objectives and the research of the key consideration factors in the space environment. The summaries of the 48 studies are summarized in the table as per the guidelines provided by Arksey et al. [19]. The key consideration factors of the instrument in the space environment can be divided into categories including the design and performance considerations. Design consideration refers to the key factors and parameters considered in the space instrument design in order to suit the extreme space environment, such as materials, duration, size, power consumption, weight can perform its designed functions in long space travel. Performance consideration focuses on whether the designed and manufactured instrument can achieve and maintain certain design functions and accuracy under harsh space weather conditions and long-term operations. The performance considers the accuracy of measurement on the collected data and signals.

Table 3. Research objectives and the key consideration factors in the space environment.

Author	Ref.	Aims and Objectives	The Key Considerations in Space
Barker	[21]	Measured changes in the laser characteristics and obtain data to understand the laser behavior and refine the instrument pointing model	Long-term laser behavior
Biasotti	[22]	Describe the design, with the preliminary phonon dynamics simulation, the fabrication, of first demonstration model	Sensitivity
Borgarelli	[23]	Development of a passive mode, implemented to measure Titan's surface emissivity	Reduced mass, low available room, low power consumption, severe environmental conditions, specific thermal control and on-ground test accessibility
Bunce	[24]	The design, performance, scientific goals and operations plans of the mercury imaging X-ray spectrometer	Design, material, size
Cavanaugh	[25]	Describes the instrument design, prelaunch testing, calibration, and results of postlaunch testing.	Performance
Clark	[26]	Review the Puck Energetic Particle Detector (EPD) design, its heritage, unexpected results from these past missions and future advancements	Review paper
Cress	[27]	Describes the design, development, and calibration of the Falcon Solid-state Energetic Electron Detector (FalconSEED)	Geosynchronous environment
Delkowski	[28]	Develop manufacturing methods for next generation of advanced composites for space instrument	Materials (composites)
Dichter	[29]	Designed an instrument to measure the local space radiation environment.	Small, lightweight, and low power
Dichter	[30]	Describe the design and novel features of the instruments and discuss their calibration program	Accurate measurements
Dickie	[31]	Design, manufacture, and characterization of a new frequency selective surface (FSS) structure	Performance
Dou	[32]	A systematic investigation of the ion beam optics to optimize the design for the Harbin system	Design optimization
Gilbert	[33]	Demonstrate an optimized design of a linear-electric-field time-of-flight technology that can be used to obtain a high signal to noise	Signal to noise, size or complexity
Godet	[34]	Study the instrument background and sensitivity of the coded-mask camera	Optimise the performances
Goldsten	[35]	Overview the gamma-ray and neutron spectrometer and describes its science and measurement objectives, the design and operation of the instrument, the ground calibration effort, and early in-flight data.	Thermal behavior, performance
Hall	[36]	Optimise the device design to suffer minimum impact from radiation damage effects	Radiation
Han	[37]	Describe the design and capability of the differential accelerometer to test weak space acceleration	Electrostatic suspension, electrostatic motor
Hsiao	[38]	Design and fabrication of optical thin films for remote sensing instruments	Optical stability
Hu	[39]	Investigate the instrument design to measure the mesospheric and thermospheric wind velocities	Mesospheric and thermospheric wind velocities
Hudson	[40]	This paper presents the current design of the accelerometer, specifically the critical areas for the instrument design, integration, and final performance requirements.	Accurate measurements

Table 3. Cont.

Author	Ref.	Aims and Objectives	The Key Considerations in Space
Koehn	[41]	Discuss the design and prototype tests of the fast-imaging plasma spectrometer (FIPS) deflection system	Lightweight, fast, and have a very large field of view
Koga	[42]	Discuss the results of the engineering model (EM) and its properties	Particle and plasma
Krebs	[43]	Develop the mercury laser altimeter	Space-flight environmental tests
Lepri	[44]	Discuss an adaptation of the fast-imaging plasma spectrometer (FIPS) for the measurement of negatively charged particles.	Design modification
LIFE	[45]	Developed an automated, miniaturized, integrated fluidic system for in-situ measurements of gene expression in microbial samples	Biological validation
Lindstrom	[46]	Design a new sensor compact environmental anomaly sensor risk reduction (CEASE-RR) for anomaly attribution	Calibration and planned flight experiment, radiation environment
Ling	[47]	Carry out the environmental adaptability design and analysis	Mechanical property and the thermal environment
Liu	[48]	Research on the effects of the space environment on the welding technology	Microgravity, vacuum conditions, and temperature differences
Lopes	[49]	Understand how each component interferes with sensitivity and response time of the instrument depending on its design, material, volume, and thermal contact.	Thermal behavior, design, material, size, performance effect
MacDonald	[50]	Extrapolate the background response to the inner magnetosphere, a highly relevant instrument design parameter for future missions to this region.	Response to the inner magnetosphere
Magnes	[51]	Describes the magnetometer instrument design, discusses the ground calibration methods and results.	Avoiding strict magnetic cleanliness requirements, dynamic stray fields
Mauk	[52]	Describe the science objectives of the Jupiter Energetic Particle Detector Instruments (JEDI), the science and measurement requirements, the challenges that the JEDI team had in meeting these requirements, the design and operation of the JEDI instruments, their calibrated performances, the JEDI inflight and ground operations, and the initial measurements of the JEDI instruments in interplanetary space	Performances
Moretti	[53]	Present a low-cost, low-weight instrument, thus particularly fit to space applications, capable of providing stability and sensitivity of signals on long-term observations.	Stability and sensitivity of signals on long-term observations
Ostgaard	[54]	Describe the scientific objectives, design, performance, imaging capabilities and operational modes of the modular X- and gamma-ray sensor (MXGS) instrument.	Instrument performance, imaging capabilities
Rothkaehl	[55]	Design of the instrument for monitoring the electromagnetic ecosystem for space weather purpose	Ionospheric plasma property and artificial noises
Sadrozinski	[56]	The Gamma-ray Large Area Space Telescope (GLAST) instrument designed for high sensitivity, high precision gamma-ray detection in space.	High sensitivity, high precision gamma-ray detection
Schlemm	[57]	Summarizes XRS's science objectives, technical design, calibration, and mission observation strategy.	X-ray
Soli	[58]	Presents radiation dosimetry results from the radiation and reliability assurance experiments on the Clementine Spacecraft and Interstage Adapter Satellite.	Performance
Swinyard	[59]	Discuss the performance of the ten doped germanium photoconducting detectors on the infrared space observatory long wavelength spectrometer	Performance

Table 3. Cont.

Author	Ref.	Aims and Objectives	The Key Considerations in Space
Thuillier	[60]	Performances of the WINDII, a Michelson interferometer used to observe wind and temperature in the upper mesosphere and thermosphere are shown and analyzed.	Performance
Warren	[61]	Describes the design, build, calibration, and initial measurements from a new laboratory instrument	Performance
Wei	[62]	Presents the special technologies applied, for the solar X-ray spectrometer, and the first pre-flight calibration results	Solar X-ray and energetic charged particles
Wesolek	[63]	Design, fabrication, simulation, and testing of the instrument front end that consists of a collimator, parallel plate energy analyzer, and energy selector mask	Small-scale, energy analysis
Wise	[64]	Describes the design, fabrication, and testing of the primary subsystems of the instrument.	Critical superconductive properties
Wright	[65]	Describe the rationale for the project, the instrument design, and the quality of the data	Mass, volume, and power constraints
Xiong	[66]	Overview the calibration algorithms, operational activities, on-orbit performance, remaining challenges, and potential improvements.	Performance
Zanoni	[67]	Investigate the performance of a radiatively cooled instrument	Performance, thermal behavior
Zurbuchen	[68]	Review the innovation triggers in the context of the design literature and with the help of two case studies	Review

4.3. Product Innovation and Design

For the innovation concept of product design in a tough space environment and mission, the findings of the study indicated that there is a relationship between innovation, product design, and manufacturing of the space instruments. Figure 2 illustrates the number of articles showing the relationship between design, manufacturing, product innovation. Most of the reviewed articles demonstrated the relationship between instrument design and fabrication. Most of the instrument innovation and related to the instrument design.

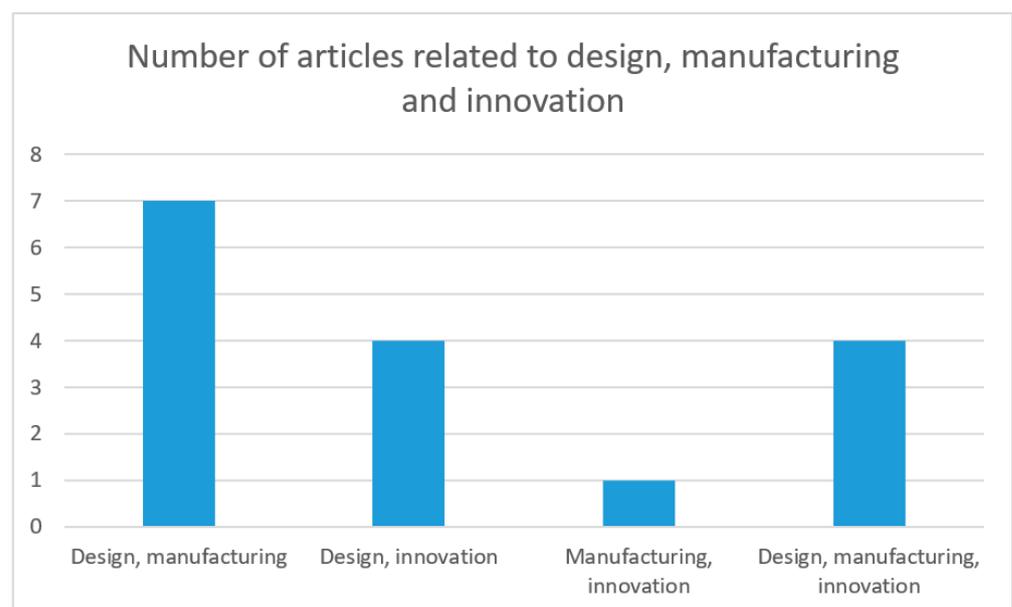


Figure 2. The number of articles demonstrates the relationship between design, manufacturing, product innovation.

Jiao et al. [69] indicated that the process of outgassing in space is a unique phenomenon in space instruments that can cause negative impacts on scientific exploration missions, high-voltage devices, and spacecraft optical systems. According to the authors, to mitigate the negative impact caused by outgassing, there is a need to develop a transient and long-term physical model of outgassing. This would be by developing new testing methods by combining the outgassing tests with the outgassing compound analysis, as well as on the improvement of the existing product design and manufacturing technology.

Dichter et al. [30] describe the next generation of GOES satellites will include a new suite of charged particle instruments. The design and novel features of the instruments and discuss their calibration program in terms of accuracy of on-orbit measurements. The innovation of the instrument development made significant improvements not only in the operational measurement of the space environment but also in the overall performance of the instrument covering a wider range of measuring abilities and lower power consumption compare with the previous version of the instrument.

Koehn et al. [41] discussed the design and prototype tests of the fast-imaging plasma spectrometer (FIPS) deflection system. The major piece of innovation is to improve the instrument to enable a larger instantaneous field of view. This novel design also enables a lightweight and fast product. Koga et al. [42] designed the engineering model (EM) and investigated its properties. A new neutron monitor instrument is designed to understand the particle acceleration mechanism at the solar surface. Life et al. [45] design a new biological system that can be deployed in near future for space missions. platforms other than the ISS to advance biological research in space. It can also prove useful for numerous terrestrial applications in the field. The novel instrument provided an automated, miniaturized, integrated fluidic system for biological validation.

4.4. Product Innovation and Manufacturing

As illustrated in Figure 2, the manufacturing of the instrument related to product innovation was usually associated with product design. Delkowski et al. [28] developed a new manufacturing method that was used to enhance polymer and composite structures in spacecraft. The novel approach of composite materials led to research and innovation over many decades. The new manufacturing of composite materials featuring 10–20 times greater resistance to cracking without affecting the stiffness of dimensionally stable structures.

Another research associated instrument innovation with the product design and the fabrication. In Clark et al. [26], new foil manufacturing processes were reviewed to discuss the association of high-voltage anomalies and the use of curved foils on recent Puck EPD designs. Han et al. [37] demonstrated the preliminary work on the development of the first instrument prototype. The space accelerometer is a newly designed instrument proposed to operate onboard China's space station. The new prototype was tested under a weak space acceleration. Modeling and simulation were performed to test the electrostatic suspension and electrostatic motor based on attainable space microgravity conditions. Noise evaluation was also performed to evaluate the performance of the instrument. This development confirmed several crucial fabrication processes and measurement techniques for the future design and development of space accelerometers.

Wesolek et al. [63] designed and fabricated a new version of a space environment that re-designed the one run in 2008. The redesigned system presented a lower cost, lower weight that fits space applications and long-term operations. The newly designed and fabricated instrument could provide stability and sensitivity of signals.

4.5. Product Design and Reliability

In the design of the space instrument, reliability is another key consideration concerned by the product designer. Indeed, the design and manufacturing of the instrument is usually relating the reliability of the product. For innovative product design improving the reliability of space instruments, García-Pérez et al. [2], found that the transient analysis performed on the STEP instrument provided accurate simulations of the shock environment.

The finite element method had higher confidence in the calculated results hence offering more information than the data obtained for the shock tests. Jiao et al. [69] also found that establishing a transient and long-term physical model of outgassing can help obtain the outgassing characteristics of different products. This shows that using innovation to develop new or improve the existing product designs helps increase the reliability of the space instruments.

According to Conscience et al. [70], improving the space instruments increases their reliability. The authors gave an example of the SOVAP instrument and how its improvement had increased its efficiency. According to the authors, the instrument has been improved by adding the bolometric oscillation sensor (BOS) in order to increase the time resolution. With the BOS, the SOVAP will be able to measure the albedo flux, the infrared flux of the Earth, and the solar irradiance with a smaller sampling period of ten seconds. Malandraki et al. [71] on the other hand conducted an experiment to compare the testing abilities of the space tool. The tool used microwave data that yielded no false alarms indicating that the product design of the instruments affected their reliability. Gold et al. [1] added that miniaturizing space instruments will help in improving the quality of the science from the instruments. The authors gave an example of the instrument of imageries which improved to include a version of the processing layer.

Jiggins et al. [72], found that the space radiation environment is an important factor for both astronauts and instruments. Other than the traditional shielding protection methods, the authors created a warning system for the solar particles event. The innovation in the study help to improve the reliability of the instrument by avoiding the large SPEs. Tam [3], raised the possibility of using new technology such as three-dimensional and additive manufacturing to replace the old manufacturing method which has a complex design and sub-system. The use of new manufacturing methods reduces the risk of pieces breaking off during collisions in the space environment.

Yung et al. [73] added that space instruments need to be designed in a such way that they perform reliably. The authors described an example of a new design of spacecraft made in 2011 that could provide both qualitative and quantitative measures of the composition of regolith. The SOPSYS however was designed in a such way that would enable it to the grid, sieve, transport, and measure samples of regolith in the absence of gravity. To increase its reliability, the instrument was developed with a reverse thread so that it would shroud any regolith that stuck in the mechanisms of the actuator. In this way, any stuck regolith would be pushed back to the grinding head. The author indicated that the new spacecraft provided an anti-jam solution that did not require additional mass hence increasing the reliability of space missions

5. Conclusions

In this study, we have explored the influences of innovation and reliability in the product design of space instruments. This was performed by conducting a review of previously published articles regarding space instruments and analyzing these articles to investigate their findings and review. PRISMA was used to search the articles systematically. The results in the study indicate that the product design of the space instrument was directly influenced by the innovation. This is because the space instrument is usually very complex and consists of many factors considering the complex situation of the deep space environment. On the other hand, the products are difficult to be found from the traditional design of a product. The study also found that the reliability of the instruments is directly influenced by the degree of innovation and product design of the space instruments. It was determined from the examples gathered in various literature sources that all innovation processes led to an improvement in the reliability of the instruments. This study is important to formulate the critical factors in the design and development of a space instrument that is important to develop the smart manufacturing protocol in the field in the future.

The current review focuses on articles about space instruments as well as product innovation, design. The criteria for inclusion are based on current trends in space exploration

and product innovation. The keyword search focuses on the setting of the three themes mentioned above. However, product design and fabrication or manufacturing technologies are closely related but not included as one of the keywords in the search. Fabrication and manufacturing are not included because the keywords are too specific generating a small number of search results, particularly focusing on the space environment. As such, the screening processes have to be performed manually leading to less objective conclusions. In the future, more databases can be included in order to enhance the searching results and related articles. On the other hand, the product design is usually related to the reliability issue, particularly in space devices and instruments. Thus, a further review can be conducted to summarize whether product innovation, design, and reliability are correlated and affect the performances of space instruments. It is recommended that future research can also be made related to the performance and design of the space instrument. Lastly, instruments that are used in the space environment may include various interpretations such as near space, deep space, orbits, planetary missions, etc. These keywords may also be included in future review studies.

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