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HISTORICAL EVOLUTION OF SPACE SYSTEMS

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ABSTRACT

Since the launch of Sputnik in 1957, thousands of satellites and space probes have been sent into space. The typical spacecraft subsystems were subject of steady technology improvements during the last five decades, which led to many changes in design and layout.
Darwin taught us that biological systems adapt and improve by a process of natural selection, known to us as evolution. The question rises if similar forces lead to an evolution within the technical world of spacecraft engineering? Can technical systems evolve over time so that one can call it technology evolution? Influences like technology S-curves, trend analysis, disruptive technology innovations, technology maps, space system failure studies and different subsystem development ratios are only a few factors that need to be considered in order to answer the question.
The results presented in this paper are based on the intensive research and analysis of a specially created database, fed from several (smaller) databases containing technical specifications (mass & power budgets) of hundreds of spacecrafts. The focus was set on exploration systems, which were analysed with different regression and correlation algorithms in order to reveal specific trends of a spacecraft subsystem as a function of time.
Analysing the evolution of spacecraft systems has two main purposes: To give technical guidance for future spacecraft designs (performed e.g. in Concurrent Engineering studies) as well as to establish a system to evaluate which technologies are worth investing in, depending on their overall technology maturity. The paper was prepared within the Department for System Analysis Space Segments at the Institute of Space Systems (German Aerospace Center - DLR) in co-operation with the University of Applied Sciences, Bremen (Germany).

INTRODUCTION

The past 50 years have seen rapid increase in the speed of progress in various technological fields. The development and improvement of devices, like television, telephone, cars, computers or mobile phones is very familiar to all of us. Every day we benefit from the improvements engineers and scientists have achieved. But how did such a technological system evolve? How is progress achieved and assured? And where will it lead us eventually? How was the technical development of one individual subsystem carried out? Which principles (objectives and requirements) were crucial during the development? Are there temporal or causal relations between the individual subsystems in term of technology evolution? Were there technology leaps in the evolution of spacecraft and their subsystems? Can future trend for space flight be detected, and hence can guidelines be educed for a successful technology management from them? To frame an answer, a general literature research on technology development and evolution, as well as on analysis of technology evolutions in space flight, is necessary.

TECHNOLOGY EVOLUTION

Natural selection is the driving force of evolution in nature. This theory was founded by the natural scientist Charles Darwin in 1859 with his book “The Origin of Species”. [1], [2] He argues that this natural selection is triggered by randomly appearing attributes or characteristics depending, which give an advantage to the life form or species they appear in. This advantage is dependent on the environmental conditions the organism is living in. It is given onwards to the next generations, by which the chance of survival of that given species is increased.
Hill argues that life itself laid the basis for further evolution through technology. [3] Because human abilities are limited to a certain level, the technological progress continues the natural evolution to overcome these limitations. Hill underlines this assumption by providing the example of the human eye, which, al-

though being a very powerful instrument, is limited in its ability to see objects very far away (e.g. other planets) or very small objects (e.g. atoms). In order to overcome this natural limitation the technological evolution has developed devices to help improving the human vision.
Today however, the aim of a new technology is usually defined before it is being developed and the given resources are used efficiently to achieve the given goal.
Generally speaking, technological progress is directed towards an ideal state as Hill describes it. [3] A good way to reach this ideality, or to get at least near it, is the orientation on similar systems in nature. Such systems went past a development lasting millions of years through biological evolution and are usually very close to an ideal design, if not having reached it. Altschuller defines an ideal system where attributes such as mass, volume and surface approaches zero, while the ability to fulfil a certain performance is not reduced. [4] But this being only a general rule, does not explain how technological progress is systematically achieved.
Hill gives a good example of technological enhancement by increasing the degree of efficiency, referring to the development of the steam-engine. The machine was enhanced by James Watt, who identified weaknesses in the steam-engine design by Newcomen. The redesign resulted in an increased performance with less energy consumption, hence an increase of the degree of efficiency. [3]
The example illustrates that an increase of the degree of efficiency is achieved by further developing an existing design. This is an important characteristic of technological evolution. There has to be some kind of source it is based on. The most basic source being a good idea, as we heard before. Hill calls the enhancement of an existing design, quantitative enhancements. But even if the degree of efficiency of the steam-engine would have been enhanced a hundred times, it would still be based on the same technical principle of using pressurized steam as a working medium. A qualitative enhancement, as Hill describes it, is achieved when a new principle is being introduced. In the case of the steam-engine the qualitative enhancement was achieved when, for example, the electro-dynamic principle of the electric motor was introduced. The development from the quantitative enhancements of the efficiency of the steam-engine to the qualitative enhancement by the principle of electro-dynamics is shown in Figure 1.

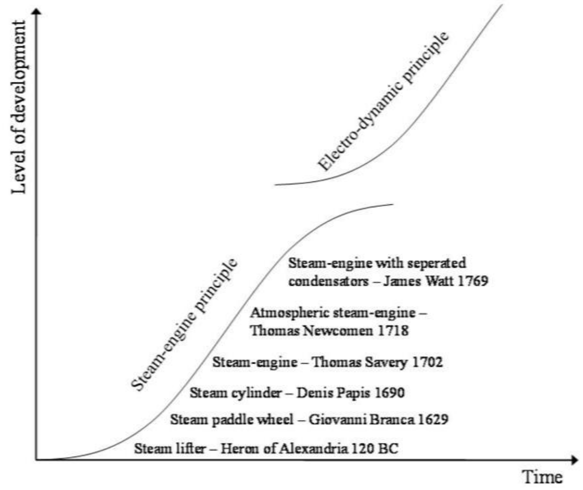


Figure 1: Development of the steam-engine [3]

From Figure 1, the so called S-curve of a product life-cycle can be obtained. As already mentioned before, most products have a lifecycle that can be divided into three stages: introduction phase, growth phase, and saturation phase.
Prof. Gemünden provides a more general and slightly better illustration of the technology S-curve. [5] In Figure 2 shows the transition from one technology to the next by three different S-curves. Each curve represents a new technology, which was shown by the S-curve of the electro-dynamic principle in Figure 1.
Old technologies are only abandoned if new technologies are more promising and by adapting them, ensure technological progress. An example would be the progress from Vinyl records, to music cassettes, to digital media like CD-ROMs and then finally to MP3s.

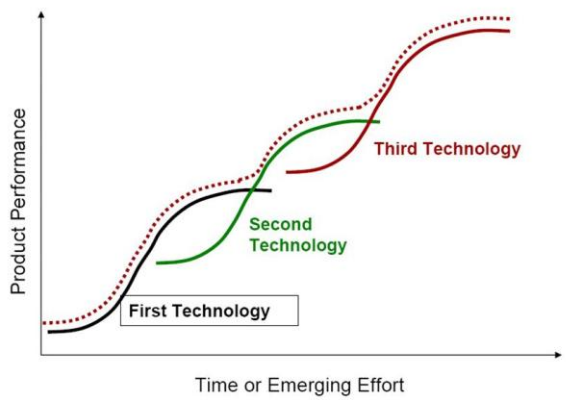
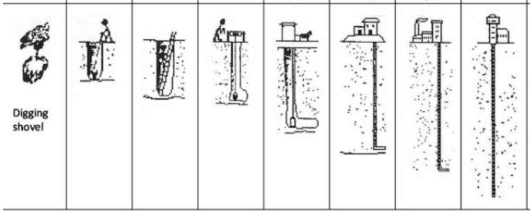


Figure 2: Conventional technology S-curve [5]

Table 1 illustrates a generations-chart describing the evolution of mining, based on the mole as the natural archetype. The different generations represent different principles of mining.

Table 1: Generations-chart - evolution of mining (according to [3])

Nature	1st Generation	2nd Generation	3rd Generation	4th Generation	5th Generation	6th Generation	Current state of technology	Trends
Mole	Mining by hand	Mining with ladders	Mining by decoiler	Mining by horse-capstan	Mining by water wheel	Mining by steam engine	Mining by electric-motor	
Digging shovel								• higher mining capacity • higher mining speed • higher efficiency



One can see that in the first and second generation mining was done by hand and ladder, in the third and fourth generation first devices like decoiler and the usage of horse-capstans were introduced. The fifth, sixth and the current generation are using the water wheel, steam engine and eventually the electric-motor to support mining.
Technological evolution does not follow the same principles as the biological evolution, but it is linked to it. The needs emerging from the biological evolution set the path for technological progress. The development and introduction of new technologies is dependent on the human creativity, which is a direct cause of the developing human brain, resulted from biological evolution.
Many great inventions in human history took place out of curiosity, but in the modern world technological evolution are largely driven by the demand for it. [6][7][8]
The trend of this demand is towards technologies with

- Higher performance
- Increased autonomy
- Miniaturization
- More electronics
- Increased artificial intelligence / smarter technologies
- Lower power consumption.

SYSTEM ANALYSIS & SEGMENTATION

In order to manage the vast diversity of space activities, a proper classification offers an overview of the research field and provides a raster, which will be beneficial for the subsequent analysis. The classification is determined according to the mission layout, which has a significant effect on the design and the configuration of the system. This leads to each classification sector being divided into several space systems, according to their mission purpose. Size, mass, thermal protection and the percentage of propellant for example can change substantially with the destination and the scientific goal.
In summary, space systems are here categorised into earthbound systems, which circle in earthy orbits, exploration systems, which travel to other planets, asteroids and comets, and into manned space systems, which allow scientific research and enable living in space, as well as human transportation and cargo. Figure 3 provides a customized overview of this classification of space systems, with an emphasis on the space segment.

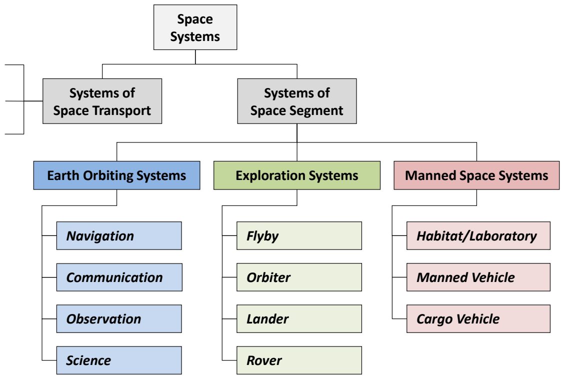


Figure 3: Space system classification according to present study [9]

After having segmented the space sector, a closer look at a spacecraft's system itself is useful. During investigation and research survey of this investigation, the following six level hierarchical system was worked out during this investigation:

- Idea and ambition (I)
- Architecture (A)
- Missions (M)
- Spacecraft (S/C)
- Subsystem (S/S)
- Component (C)

A seventh and deeper level after the spacecraft's components, which is not mentioned here, are the technologies referred to as the potential implementation possibilities. This level is more an inherent characteristic of the component level as well as the overlying system levels.
After the idea is expressed and approved by the respective authorities, the specific goal of thie idea has to be defined (e.g. "we fly to the moon"). This basically means that the participating parties have to design a strategy how the goal can be achieved in the

best way. The result of this procedure is a general architecture. The architecture for example defines how many and what kind of missions are needed to fulfil the target. The missions build up on the scientific and technological experience of the previous missions, to get an advantage from ‘lessons learned’ and scientific investigations. Also the ground segment as well as the launch vehicle is defined in the mission architecture.
To perform the missions of the project architecture, generally multiple spacecrafts (S/C) are necessary to fulfil the mission objective (e.g. Cassini/Huygens). The spacecraft of a mission occasionally serves different purposes, which leaded to differences in the assembly of the different spacecraft.

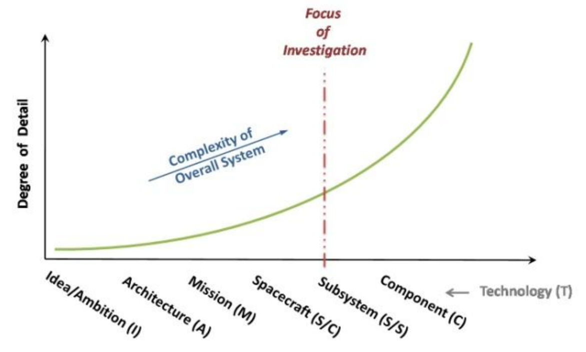


Figure 4: Level of detail in mission hierarchy / Focus of investigation [9]

Figure 4 shows the level of mission architecture already mentioned before. This paper focuses on the architecture level of subsystems by describing the technological evolution in the course of the history of space flight. Furthermore, the investigation is limited to fly-by and orbital exploration systems only (compare Figure 3). Excluded are rover and lander systems. Spacecraft remaining in Earth orbit, launch vehicles and manned space missions are also left out of consideration.
The function of a spacecraft can only be assured by the correct operation of all necessary subsystems (S/S) of a spacecraft. The subsystems are build-up of a diversity of single parts, which, as a total assembly, present the subsystem itself. An example for an important subsystem could be the power supply of the spacecraft. Power can e.g. be provided with solar panels or just batteries. The function of the subsystem is achieved by several components (C) operating together.
A subsystem’s purpose can be realized in different ways, using different technologies (T). As an example, possible technologies for power supply via solar cells could be one of the following:

- Monocrystalline silicon solar cells
- Polycrystaline silicon solar cells
- Multiple junction solar cells
- Thin film solar cells

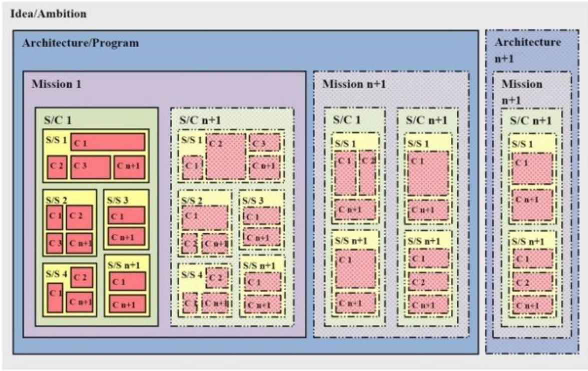


Figure 5: Hierarchy of space systems [9]

Figure 5 shows the mentioned design of the proposed hierarchical system. It demonstrates the six different levels.

DATA MODEL & ASSUMPTIONS

The survey is part of the Concurrent Engineering Reference Database (CERD) initiative of the German Aerospace Center (DLR) Bremen. CERD will support engineers during their design work at DLR’s Concurrent Engineering Facility (CEF).
The database was build up during the investigation mainly with *secondary data*, like databases and reports. But also interviews and personal correspondence with experts have contributed to the database. The different sources were:

- Databases [10][11][12]
- Missions’ websites
- Information homepages and reports
- Interviews and personal correspondence

During the investigation, one has to consider some assumptions and limitations, which set limits to the results and findings and narrow the application range of this research work:

- The data model lists nearly all launched exploration missions from 1958 until today. Of around 200 launched exploration missions, listed in the database, about 50 allow a detailed data examination.

- The database shows a lack of exploration missions, and thus a lack of mission data, in the 1980s. This is possibly caused by the cancelled Apollo missions in 1970, the concentration on the Skylab missions in the early 1970s and on the Space Shuttle development, and by emerging technologies and increased demands on communication satellites.
- The database layout is performed according to the space systems classification, developed in the previous chapter (see also Figure 3 & 4).
- American, European, as well as Japanese exploration missions are primary considered in the database due to a lack of Russian (and former Soviet), Indian and Chinese mission data.
- Soviet exploration missions are just mentioned as a relation for a comparison for the evolution of dry mass, number of launches and examples of destination.
- Rover, lander and additional probes carried by a cruise probe are considered as spacecraft payload.
- Mechanisms, pyrotechnics and harness masses are summed up with the structure mass, as a result of already combined masses in reports and databases.
- The listed bus mass includes all subsystem masses, the dry mass additionally contains the payload and instrument masses, the launch mass is the wet mass and therefore contains also the propellant mass.
- Indications of weight in pounds are converted in kilograms. The conversion between the parameters is carried out using a factor of 0,453592 (1lb ≡ 0,45kg).

PRELIMANARY FINDINGS

The examination of the history of exploration mission enables a first observation. Figure 6 shows the outcome of the first exploration probes database examination. The mission lifetime [month] (y-axis) is illustrated as a function of time (calendar years 1958 to 2010). A linear regression line demonstrates the correlation of the parameters. The already mentioned lack of missions in the 1980s is visible in the diagram. It is evident, that the mission duration increases over the last 50 years. New technology and increasing requirements on the mission objectives lead to the demand on longer lasting missions with a higher number of achievements and outcomes. However, the demonstrated graph (cf. Figure 6) only presents the planned mission lifetime.

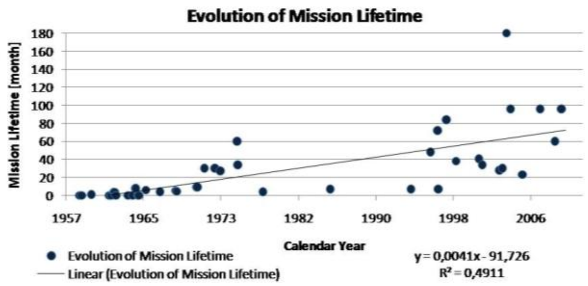


Figure 6: Evolution of mission lifetime of exploration systems from 1958 to 2011

Also the history of bus and payload masses of the past 50 years allows a statement of a possible trend. Figure 7 depicts the evolution of bus and payload mass [kg] (y-axis) from 1958 to 2010 (x-axis). While the bus mass (green dots) increases steadily, the absolute payload mass (red dots) seems to remain nearly constant.

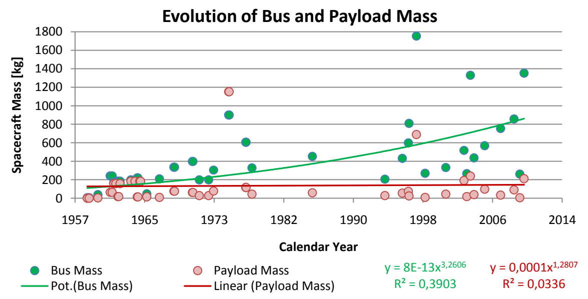
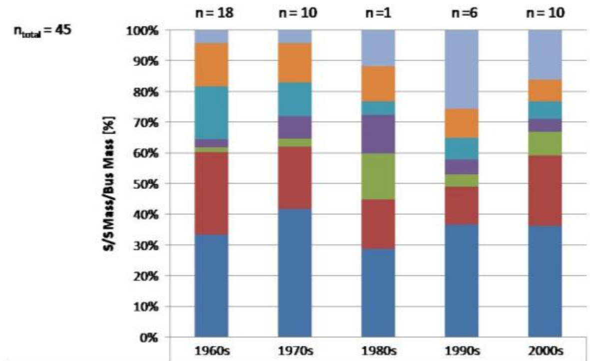


Figure 7: Evolution of bus and payload mass of exploration systems from 1958 to 2011

Longer mission lifetimes normally lead for example to larger propellant masses, which increases the tank masses of the propulsion system. Furthermore, longer mission lifetimes mean more radiation, shadow and sun phases affecting the spacecraft, which requires a better and heavier thermal control subsystem. Such impacts of increased mission lifetimes as well as the higher importance of system redundancy lead to rising bus masses. Redundant systems, which mean a system is covered double, secure the operation of a system, in case of failure.



	1960s	1970s	1980s	1990s	2000s
Propulsion	2,92%	2,54%	9,81%	21,13%	13,52%
Attitude Control	9,83%	7,88%	9,76%	7,68%	5,90%
Communication	11,93%	6,65%	3,77%	5,84%	4,77%
Data Handling	1,89%	4,56%	10,61%	4,08%	3,47%
Thermal Control	1,07%	1,57%	12,81%	3,12%	6,51%
Power	18,70%	12,46%	13,56%	10,27%	19,08%
Structure, Mechanisms & Harness	23,41%	25,57%	24,46%	30,31%	30,44%

Figure 8: Evolution of relative average subsystem masses grouped by decades from 1960s to 2000s

Figure 8 summarizes the evolution of relative average subsystem masses grouped by decades from 1960s to 2000s, in a block diagram. The decades are shown on the x-axis of the graph, while the relative subsystem masses are given on the y-axis. Introductive to Figure 8 it has to be said that the 1980s are statistically rather unrepresentative, because the data consists of only one spacecraft (n=1).

The increased propulsion and thermal subsystem masses can be explained by the increased mission lifetimes. The slight reduction in the 2000s may be due to the new missions to the Moon, at which the spacecraft have to travel shorter distances, compared to the Mars missions in the 1990s.

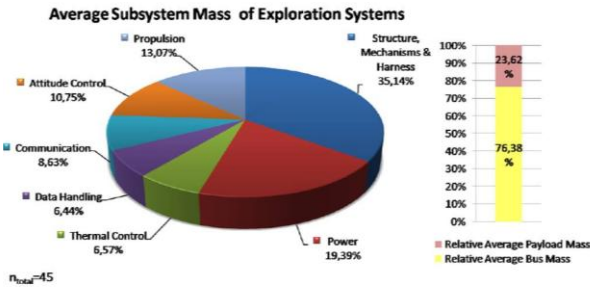


Figure 9: Total relative average subsystem mass of space exploration systems from 1958 to 2010

Derived from these findings, Figure 9 shows the total average subsystem masses over the last 50 years. The figure depicts that over the last five decades 50% of an exploration spacecraft were structure, mechanisms and harness together with the power subsystem. If we compare that figure with the respective figures of the 1960s (54%) and the 2000s (47%) the slight declining trend becomes evident.

ANALYSIS METHOD

To examine the changes in subsystem mass over the last 50 years, as well as with regard to future missions, planned and developed until 2015, a regression and correlation analysis is carried out, resulting in a regression function with a regression line, as well as a correlation coefficient for each subsystem.

The evolution of subsystem masses over time is examined by showing their development over the last 50 years. Because of differing mission layouts it is necessary to form a ratio for each subsystem in dependence of the bus mass, to make the missions comparable. This means a division of the respective subsystem mass (e.g. power) through the bus mass of that spacecraft. By carrying out these types of statistical analysis, possible correlations and a trend analysis can be discovered, from which future developments could benefit.

The highest precision of the linear regression is reached, when the estimation of values for a and b minimizes the sum of the squared residuals (e_i^2). [13][14]

This is calculated by:

$$a = \bar{y} - b\bar{x} \qquad [1]$$

and

$$b = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sum(x_i - \bar{x})^2} \qquad [2]$$

(a = axis interception point; x_i = measured declaring variable; $\bar{x}$ = mean value of measured x_i; y_i = measured response variable; $\bar{y}$ = mean value of measured y_i; b = slope)

It can be calculated by dividing the difference of the sum of squares of residuals and the sum of squares of errors through the sum of squares of residuals:

$$R^2 = \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2} \qquad [3]$$

(R^2 = determination coefficient; $\hat{y}$ = predicted response variable;
y_i = measured response variable; $\bar{y}$ = mean value of measured y_i)

The Bravais-Pearson correlation coefficient is calculated by dividing the covariance of the variables x and

y through the standard deviations of the two variables x and y.

$$Cor = \frac{\text{Cov}(x,y)}{\sigma(x)\times\sigma(y)} \quad [4]$$

(Cor = correlation coefficient; $Cov(x,y)$ = Coviariance of x and y; $\sigma(x)$ = standard deviation of x; $\sigma(y)$ = standard deviation of y)

The covariance *(Cov)* of two variables is the sum of the product of the difference from the measured value of the variables of their respective mean values:

$$\text{Cov}(x, y) = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y}) \quad [5]$$

($Cov(x;y)$ = Coviariance of x and y; n = amount of measurements; x_i = measured declaring variable; $\bar{x}$ = mean value of measured x_i; y_i = measured response variable; $\bar{y}$ = mean value of measured y_i)

The aim of this research work is to make a statement about a possible trend in evolution of exploration spacecraft systems. Although the gathered data represents just a quarter of all listed exploration missions launched until today, it is possible to show an evolution trend of the last 50 years and possible trends of subsystem mass growth. The figures of the following chapter are based on 42 to 49 data points.

The number of data points does not allow a trend analysis separate by mission destination, but it enables the confirmation of a general evolution.

EVOLUTION OF EXPLORATION PROBE'S SUBSYSTEMS MASS

This chapter will visualize results of the data analysis about the subsystem masses evolution of exploration and deep space missions over the last 50 years. In order to make the mission data comparable, a normalization process has to be applied and the subsystem masses are shown as a percentage of the bus mass of the spacecraft. Thus, comparability between different missions, with every spacecraft having a different bus mass, is enabled. This chapter only shows a small section of the full analysis. In order to see all mass evolution charts, please refer to source [9].

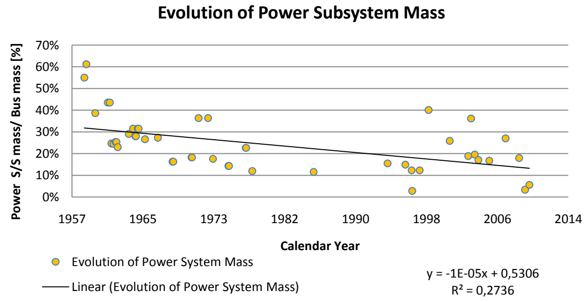


Figure 10: Evolution of power subsystem mass of exploration systems from 1958 to 2010

Figure 10 illustrates the power subsystem mass as a proportion of the bus mass on the y-axis, in relation to the time [calendar years], on the x-axis. The regression line is shown as well as the determination coefficient.

The last five decades show a slight decrease of relative power subsystem masses although spacecrafts still show a diverse proportion of power subsystem masses of the overall mass. It is not easy to compare the power subsystems with those of later, more sophisticated probes. The reason for this is the first probes being only equipped with primary batteries later also small solar arrays as a source of power. More modern probes however have large solar arrays and secondary batteries, or even radioisotope thermoelectric generators (RTG), which are very differing technologies with different system weights. The use of solar arrays is also influenced by lightweight technologies, as they have a high proportion of structure holding the solar panels.

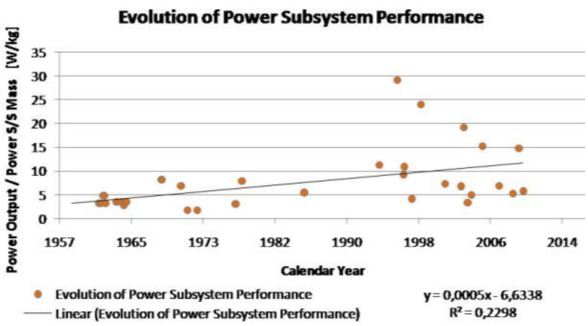


Figure 11: Evolution of Power Subsystem Performance of exploration systems from 1958 to 2010

Figure 11 shows the evolution of the power subsystem performance. It depicts the spacecraft's power output [W] per kilogram mass (y-axis) over the calendar years from 1958 to 2010 (x-axis). The data points of 17/02/1996 (*NEAR Shoemaker* mission to asteroid Eros) and 24/10/1998 (*Deep Space 1* mission to comet

Borrelly) with aberrant high values of 29,2W/kg and 24,07W/kg seem to present outlier. Looking at Figure 11 it is evident that there has been a slight increase in the power output per kg of power subsystem mass. This could be a reason for the decreasing power subsystem mass, illustrated in Figure 10.

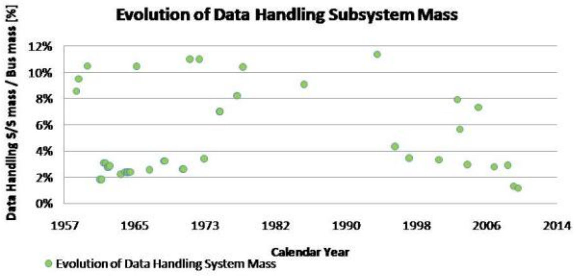


Figure 12: Evolution of data handling subsystem mass of exploration systems from 1958 to 2010

Figure 12 shows the evolution of the data handling subsystem masses. The mass of the data handling subsystem as a proportion of the bus mass can be seen on the y-axis, while the timeline in years is shown on the x-axis.

Between the 1960s and 1970s the masses, as proportion of the bus mass, of the data handling subsystem seem to be split into two groups. One with rather low data handling percentages of about 2% (Mariner and Ranger missions), and another group with a percentage of about 10% (Pioneer). Today the mass proportion is located between those two groups at 3% to 8% of the overall bus mass.

There is no visible evolution noticeable. In average the percentage of the data handling subsystem mass of the overall mass seems to be rather constant.

Although there is no visible evolution in terms of an increase or decrease of the proportion of the data handling subsystem of the bus mass, that does not mean that there have been no enhancements. They may well have been qualitative enhancements, instead of quantitative increase in mass, by the increase of the technology efficiency.

Figure 13 depicts the evolution of the relative communication subsystem mass (y-axis) over the last 50 years (x-axis). A linear regression line, along with the determination coefficient is also shown.

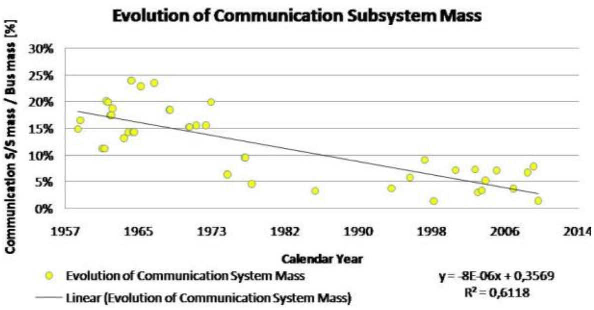


Figure 13: Evolution of communication subsystem mass of exploration systems from 1958 to 2010

Besides the lack of exploration missions in the 1980s, which can again be seen in this figure, two main clusters of data points are visible. The first is beginning in the end of the 1950s, lasting to the early 1970s, ranging from a percentage of almost 25% to about 11%, the second being situated between the mid 1990s and today, ranging from about 8-9% down to about 1%. It shows a clearly significant decrease of the communication subsystem proportion of the bus mass.

Accordingly, the communication technologies show, that for example same bit rates require decreasing output power; respectively rising bitrates are transmissible with the same output power. Lower output power need different amplifier, like with semiconductor technologies, which enable lighter components. Changes in wave band (spectrum), e.g. from S-band to X- and Ka-band, mean smaller wave length, and consequently smaller components like antennas.

But also the evolution of electronic devices allowed producing smaller components, which are lighter and provide a higher performance at the same time. The development from normal soldering joints to surface-mounting technology (SMT) with so called surface mounted devices (SMD), lead to weight savings due to the electrotechnology development itself. All listed factors may have influenced the decrease of communication subsystem masses towards smaller proportions of the bus mass.

INTERRELATION OF SUBSYSTEMS MASS BEHAVIOR

The evolution of the subsystem masses are affected by a diversity of unknown parameters. Some parameters can only be assumed. To understand the influences, which affect the subsystem's masses, interrelations between subsystems are examined in this chapter. A subsystem's reaction or influence on another subsystem's mass change, can give an idea on possible dependencies. Consequently, a possible influence parameter on the evolution could be identified.

From the high diversity of possible subsystem varieties, only the significant ones are presented, showing at least a correlation coefficient higher or equal than 0,3 for a positive correlation, or lower or equal than -0,3 for a negative correlation. According to some authors, such a coefficient means at least a correlation of medium strength between the two examined subsystem mass behaviours. [15][16]

Figure 14 describes the relative AOCS mass as a function of the relative communication subsystem mass. The relative AOCS mass is plotted on the y-axis and the relative communication subsystem mass on the x-axis. A linear regression line with y=0,7585x+0,0115 shows the relation of the subsystem masses with a determination coefficient of R^2=0,38 and a correlation coefficient of about Cor=0,61. Most of the data points show the relative AOCS masses between 1% and 8% being linked to the respective relative communication masses between 1% and 10%.

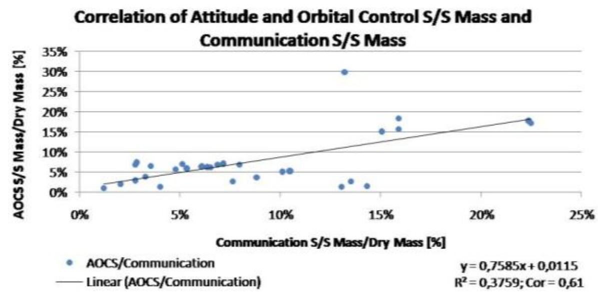


Figure 14: Correlation of attitude and orbital control S/S and communication S/S of exploration systems (1958 to 2010)

The correlation coefficient of Cor=0,61 shows a rather strong linear relation between the two variables. The determination coefficient of R^2=0,38 furthermore explains a medium strong dependency of the relative AOCS mass on the relative communication mass. This could mean if the relative mass of the communication system is increasing, the relative AOCS mass has also to be increased.

Longer spacecraft antennas or bigger parabolic antennas allow a better and greater data transmission and reception. To achieve that, the transmission beam has to be more focused and narrow. In order to keep the direction focused within the narrow limitations of the beam, the AOCS has to be better dimensioned with a better performance, and thus will be heavier.

Figure 15 describes the relative power subsystem mass (y-axis) as a function of the relative data handling subsystem mass (x-axis), and Figure 16 as a function of the relative communication subsystem mass (x-axis). Both relations are shown with a linear regression line.

A cluster of relative data handling subsystem masses can be seen in Figure 15 between 1% and 4% with a relative power subsystem mass between 1% and 30%. A little less compact cluster between 6% and 10% of relative data handling subsystem mass with a relative power subsystem mass between 10% and 50%, can be seen in Figure 16.

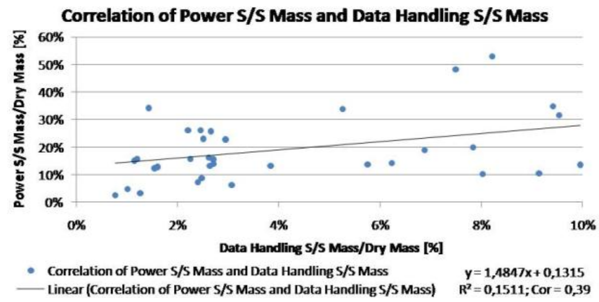


Figure 15: Correlation of power S/S mass and data handling S/S mass of exploration systems (1958 to 2010)

Both figures have similar correlation coefficients of Cor=0,39 and Cor=0,37, which respectively means in both cases a linear relation of medium strength between the respective relative subsystem masses.

The determination coefficients in both figures are rather weak with values of R^2=0,15 and R^2=0,14. So, there is only a slight dependence of the power subsystem mass towards the data handling and communication subsystem mass.

The dependency of the relative power subsystem mass towards the relative data handling mass and relative communication mass could be the increased power consumption of increasing data handling and communication systems. [6]

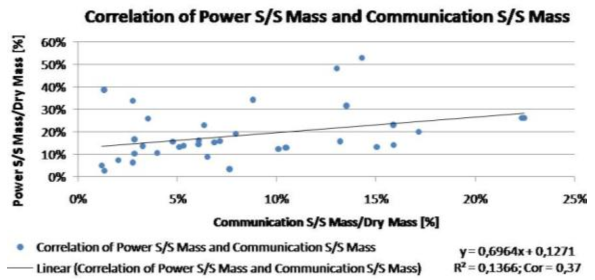


Figure 16: Correlation of power S/S mass and communication S/S mass of exploration systems (1958 to 2010)

If the relative data handling subsystem mass, perhaps due to rising thermal control requirements, increases, it could result in the relative power subsystem mass also increasing. The same could result due to rising communication system masses, possibly occurring due to rising demands on data rate transmission and receiving. [6]

CONCLUSION & OUTLOOK

As we have seen, the examination of space system evolution is of very complex nature, which is being influenced by many known and unknown factors. The consideration of general technological evolution, as well as the classification of space systems were beneficial to the research and helped to interpret the results of the data analysis. As with every other statistical analysis, the results may be subject to different point of views and by that, different interpretations. Nevertheless, some conclusions of the historical evolution of space systems can be drawn on the basis of the previous results and examinations.

Demand (e.g. commercial, governmental or military) has replaced the curiosity from the early days of technological inventions as the driver of technological evolution. The computer can be seen as the main influential technology emerging in the last century. Not only the everyday life benefited from it, also space systems became more powerful and efficient using new computer technologies. This becomes evident when analysing the evolution of spacecraft subsystems.

Each technological development usually follows an S-curve shaped lifecycle. The knowledge of such S-curves enables engineers and scientists to support and accelerate technological evolution towards the existing demand. It allows effective and cost efficient development of new technologies and gives evidence, if an existing technology is near its performance limit. This applies especially for the development of new space systems which rely on the newest and most efficient technology. To make use of the lifecycle of space systems, it is necessary to have knowledge about the historical evolution.

The last five decades have seen a change in space industry from competition between nations towards international cooperation. In order to research the historical evolution of the subsystems, which will give support to engineers for the development of future space systems, extensive research was done to obtain sufficient data. The data collection, which proved difficult due to data being not available publicised, resulted in a database of about 200 exploration missions, with about 50 allowing a detailed data examination. However it lacks data of the 1980s due to little space exploration activity.

Until today, the space age was characterized by the exploration of the inner planets of the solar systems in the first decade, followed by exploration missions to the outer planets in the 1970s. The 1980s saw very little space exploration activities, hence the lack of data in the database, which was followed by an emphasis of exploration activities towards Mars in the 1990s and increased lunar exploration activities in recent years.

The investigation of the data offered the possibility to demonstrate developments in space history like increasing launch masses and mission lifetimes. Also changing proportions of subsystem masses on the bus mass over the last 50 years could be pointed out. The relative mass of structure, mechanisms and harness, as well as data handling, do not show a substantial change over the last 50 years. This is because they are strongly dependent on the mission objective. However, percentages of thermal control and propulsion subsystems increased compared to the average over the last 50 years. The origin for this could be found in the increasing mission durations. This could imply that the existing technologies, these subsystems are based on, are near their performance limit on the S-curve lifecycle. This would require more efficient and effective technologies.

Decreasing percentages of communication and power subsystem masses, with rising system performances, are further findings of the historical research work.

In order to obtain statistical relations within the historical evolution of subsystems, regression and correlation analysis were carried out during the data analysis. This enabled to comment on the degree of linear relation and dependency of different variables. Therefore it allows obtaining possible future trends of subsystem evolution.

Table 2 summarizes the results extracted from the regression analysis of relative subsystem mass evolutions.

Table 2: Summary of regression analysis

Subsystem	Regression Function	Determination Coefficient R²	Mass Evolution Trend*
Structure	no	no	no
Power	$y = -E^{-05} \cdot x + 0{,}5306$	$R^2 = 0{,}2736$	↘
Thermal Control	$y = 3 \cdot E^{-06} \cdot x - 0{,}051$	$R^2 = 0{,}3766$	↗
Data Handling	no	no	no
Comunication	$y = -8 \cdot E^{-06} \cdot x + 0{,}3569$	$R^2 = 0{,}6118$	↘
Attitude Control	$y = -4 \cdot E^{-06} \cdot x + 0{,}2314$	$R^2 = 0{,}1218$	↘
Propulsion	$y = E^{-05} \cdot x - 0{,}2735$	$R^2 = 0{,}5543$	↗

*↗: increasing relative S/S mass; ↘: decreasing relative S/S mass; no: no trend evident

The interrelation between subsystems allows possible conclusions on influencing parameters, which lead to changes in the proportion of subsystem masses over the last 50 years of space exploration.

Strong correlations between mass proportion changes in the attitude and orbital control subsystem (AOCS) and the structure, as well as the communication subsystem were pointed out. Furthermore, interrelations between mass proportion changes between data handling and thermal control subsystems, as well as between the power and data handling subsystems, as well as between the power and communication subsystems, were demonstrated.

Table 3 summarizes the results extracted from the correlation analysis of subsystem mass change relations.

Additionally, the assumption, that increasing bus masses lead to increasing subsystem masses, independently from the payload mass, has been confirmed. Increasing subsystem masses showed a strong correlation (Cor=0,55 to 0,85) to increasing bus masses, just with little less characteristic in the thermal control and communication subsystem, as well as in the attitude and orbital control subsystem.

Table 3: Summary of correlation factors between different subsystems (S/S)

Subsystem	Structure	Power	Thermal Control	Data Handling	Communication	Attitude Control	Propulsion
Structure	1	0,02	0,03	-0,07	0,33	0,69	-0,4
Power	0,02	1	-0,05	0,39	0,37	-0,04	-0,17
Thermal Control	0,03	-0,05	1	0,35	-0,38	-0,32	-0,12
Data Handling	-0,07	0,39	0,35	1	-0,01	-0,31	-0,05
Communication	0,33	0,37	-0,38	-0,01	1	0,61	-0,4
Attitude Control	0,69	-0,04	-0,32	-0,31	0,61	1	-0,35
Propulsion	-0,4	-0,17	-0,12	-0,05	-0,4	-0,35	1

Cor = 1 / Cor = -1; Cor = 1 to 0,5 / Cor = -1 to -0,5; Cor = 0,5 to 0,3 / Cor = -0,5 to -0,3; Cor = 0,3 to 0 / Cor = -0,3 to 0

Based on the development of the past 50 years, it can be assumed that relative subsystem masses of subsystems like power or communication will decrease further. This will be possible on the basis of the future evolution of technical systems providing a higher performance level with lower requirements towards size and mass, hence a higher degree of efficiency.

Propulsion and thermal control subsystems are likely to increase in relative mass if no new and more efficient technologies are introduced. This assumption is based on the tendency of space missions having growing mission durations with several mission objectives, which require these subsystems to provide higher performance.

Because of the fundamental role of the structure, mechanisms and harness, the relative mass of this subsystem is not likely to change significantly. Nevertheless minor changes could be possible by using new lightweight structures such as composites for building the spacecraft structure. The attitude and orbital control subsystem have not seen significant changes in relative mass over the past 20 years, which seems to be a trend for future AOCSs.

The shown interrelations between subsystems will help to support future Concurrent Engineering studies at the Concurrent Engineering Facility (CEF) within the Institute for Space Systems (DLR), Germany. Subsystem mass trends and interrelationships between different subsystems will help the engineers to evaluate their calculation and estimates.

Future investigations will concentrate on Earth orbiting satellites and spacecrafts, where a bigger base of primary data is anticipated.

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