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Analysis of the DF-ZF hypersonic glide vehicle: a look at China's defense innovation system.

Abstract

On 27July, 2021, China conducted a test with the DF-ZF hypersonic glide vehicle (HGV), which orbited the Earth before reaching its target and prompting ertain US authorities to describe the situation as "worrying" (Sevastopulo, 2021). China's hypersonic weapons programme has attracted a great deal of global attention and research interest in recent years. China's development of a hypersonic weapon system is relevant because of what it provides for the People's Liberation Army (PLA), but even more so because of what it could mean for China's ability to innovate in the field of defense technology. This article examines the technological project that gave rise to the DF-ZF HGV, and using T. M. Cheung's (2021: 775-801) model of defense innovation systemsl, analyses the main factors of the Chinese system to find its potential strengths and weaknesses.

Keywords

China, Innovation, Technology, Military, Hypersonic, DF-ZF, HGV, PLA.

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1- Introduction

In 2019, China unveiled a new missile in its arsenal: the Dongfeng-ZF(东风 ,Dōngfēng, “east wind”) or DF-ZF. It is not just another missile in China’s wide range of ballistic missiles, but a hypersonic glide vehicle (HGV). The DF-ZF is the first hypersonic missile type available to the Chinese armed forces and was developed entirely in China. The development of the DF-ZF has attracted worldwide attention, and especially after a launch in July 2021 in which the missile circled the globe before hitting its target.

HGVs are designed in a way that after being launched from high altitude they accelerate without self-propulsion to hypersonic speeds, harnessing the pull of gravity, and are able to manoeuvre and maintain a low trajectory until they reach their target. China has become one of the first countries to develop an HGV and, in addition, the DF-ZF model is capable of carrying a conventional or nuclear warhead.

According to two leading Chinese experts on hypersonic technology (Cai and Xu, 2012), the technological challenges involved in developing such weapon systems are diverse and highly complex. They cover the fields of overall integrated design technology; propulsion technology (not applicable to the DF-ZF in this case); materials, processing and manufacturing technology; test and verification technology; flight control, guidance and navigation technology; and flight demonstration and validation technology. The highly complex areas of research involved in hypersonic technology are the reason why only the armed forces of Russia, China and the United States currently operate such systems.

While China’s seemingly sudden success in developing hypersonic weapons may come as a surprise to outside observers, hypersonic technology has been a key part of Chinese national security research initiatives for more than 30 years, such as programmes 863 or 973 from 1986 and 1997, respectively. In addition, an official US report from 2020 (Office of the Secretary of Defense) stated that many of the Chinese military’s missile systems were comparable in quality to those of other top international producers, and that during 2019 China had launched more ballistic missiles in testing and training than the rest of the world combined.

The fact that the People’s Liberation Army (PLA) has the capability to deploy a hypersonic missile system is highly relevant for two reasons. First, because some modern antimissile defence systems may become obsolete, leaving vulnerable what they are supposed to protect: military assets, facilities on national territory or even an aircraft carrier sailing across the ocean. It is precisely the ability to penetrate defensive systems that is the most important characteristic of hypersonic weapons and that is precisely what Chinese high command is pursuing (Zhao, 2020: 109-122). Second, and perhaps more importantly, the fact that the Chinese military posseses hypersonic missiles is evidence that China’s defence innovation system is achieving significant results.

In the article by an Arms Control Association article (Bugos, 2022), US Senator Marsha Blackburn, was quoted as saying in reference to Chinese hypersonic weapons, "what we are concerned about is falling behind". Meanwhile, the *Financial Times* (Sevastopulo and Hille, 2021), US Congressman Michael Gallagher claimed that China's military has an increasingly credible capability to threaten the United States with both conventional and nuclear attacks, raising new questions about why China's military modernisation has been underestimated.

The modernisation of the PLA through technological advances is a high priority for the Chinese Communist Party (CCP) led by Xi Jinping. In a speech at the 19th CCP Congress in 2017, the leader put it this way:

> "In order to adapt to the trend of the global world military revolution and of national security needs, we will improve the quality and efficiency of national defence construction and the army [...] so that [...] by the mid-21st century, our people's armed forces have been fully transformed into world-class forces". (Xi, 2017).

Five years later, at the 20th CCP Congress in 2022, Xi Jinping expressed himself in a different way: "Quickly elevating our people's armed forces to world-class standards are strategic tasks for building a modern socialist country in all respects. We must apply the Party's thinking on strengthening the military [...] through reform, science and technology, and personnel training. (Xi, 2022).

From these words we can see that the Chinese authorities' motivation for transforming PLA into a world-class army has shifted from a goal to match the "trend of the new global military revolution" to, in five years' time, being "strategic tasks for building a modern socialist country in all respects".

Thus, the modernisation of the PLA through "reform, science and technology, and personnel training" is now central to the foundations of the Chinese nation, as expressed by its top political leader. Moreover, this goal is entrusted to the superiority of the political model led by the CCP: "The defining feature of socialism with Chinese characteristics is the leadership of the Communist Party of China; the greatest strength of the system of socialism with Chinese characteristics is the leadership of the Communist Party of China; the Party is the highest force for political leadership." (Xi, 2017).

The question of whether China, due to its political and institutional model, has advantages or disadvantages in achieving the desired military technological superiority is currently a subject of debate among experts. Some argue that the Chinese model allows for a greater ability to work in the same direction and generate synergies, but there are also those who argue that the Chinese innovation system is hamstrung by its leaders.

Some of the most critical of the Chinese model argue that innovation cannot be controlled and directed as the Chinese authorities claim in the military sphere. The American author Matthew Evangelista argued many years ago, in reference to centralised and authoritarian countries, that "the centralised and secretive nature of the system discourages low-level initiative by inhibiting the free flow of information and imposing a hierarchy of military and research objectives" (author's own translation) (1989: 147-171).

Other authors make reference to this argument in the case of modern China. For example, British academic Kerry Brown (2014) argues that the Chinese authorities in trying to control and direct innovation in the defence field will end up slowing it down. Stephen G. Brooks and William C. Wohlforth (2016: 91-104) suggest that economic growth no longer translates as directly into military power as in the past and consider that it is now more difficult than before for rising powers to rise and established ones to fall.

On the other hand, there are other experts who take the opposite view. An example of this is the well-known political scientist Graham Allison (2021: 40) who believes that the many studies of the early 21st century were wrong to underestimate China's potential, because according to Allison, although the United States still retains military dominance, in some technological fields China is already on a par with the US.

Also Cordesman (2021) and Puglisi (2020: 74-91) also criticise the fact that it is still difficult to break out of certain paradigms that lead to the tacit assumption that the system represented by the US is superior to China in terms of generating innovation, rather than analysing in detail the comparative strengths and weaknesses of each system. This issue is very relevant today because, according to data from the OECD and echoed in a report by the European Commission, China overtook the EU as a whole in R&D investment in 2014 and is moving closer to the United States, which it already surpasses in terms of its share of the top 10 % of most highly cited publications (Preziosi *et al.*, 2019).

The research question of this article is whether China is demonstrating a capacity to generate world-class military technological innovation and what are the potential strengths and weaknesses of its defence innovation system. This will be done through the case study of the DF-ZF HGV development programme.

2. Theoretical framework

Innovation is understood as that which generates and implements new products, but also new ideas, processes and services. (Thompson, 1965: 1-20; West and Anderson, 1996: 680; Wong *et al.*, 2009: 238-251). Innovation is also associated with change (Damanpour, 1996: 693-716) or with that which makes new business opportunities possible (Du Plessis, 2007). As for the concept of defence innovation, these general ideas also apply, but need to be translated into their specific field.

The concept of the *military innovation triad* (Sapolsky *et al.*, 2009; Krepinevich, 1994: 30-42; Zabecki, 2005: 603-604; Cheung *et al.*, 2011; Ross, 2010) represented by a triangle with three vertices: technology, organisation and doctrine (Artículo 1 Figura 1).

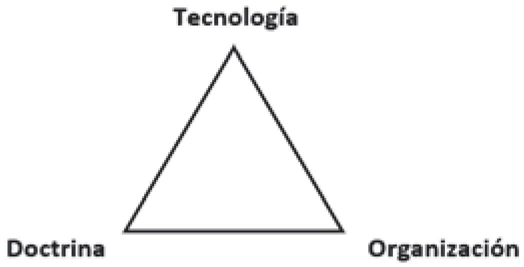

Figure 1. Military innovation triad.

Technology refers to the technical tools and resources mainly related to the weapon systems used by armies. *Organisation* refers to the structure of the armed forces and *doctrine* refers to the way in which the armed forces operate and use different weapons system. This concept is intended to explain that these three components must be in sync for there to be an effective increase in military capabilities and for military innovation to occur. Lack of progress in any of these elements renders any progress in the others ineffective. However, significant changes rarely occurs simultaneously in these three components, but rather, one leads the change while the others follow.

It is increasingly accepted that in modern armies, especially after the Gulf War, the change in technology is the leading factor that is driving and conditioning change in organisation and doctrine. (Sapolsky *et al.*, 2009; Krepinevich, 1994: 30-42; Zabecki, 2005: 603-604). None of these authors claim that there are no cases of innovation led by organisation and doctrine or that these aspects are not relevant. However, they do assert that, in the face of the rise of global technological development, these two factors tend mainly to adapt to the conditions imposed by one's own technology as opposed to that of the adversary.

Cheung, a great scholar of defence innovation, and technological innovation in particular, presents a definition of defence innovation that reflects the pre-eminence of technology:

> "Defence innovation is the transformation of ideas and knowledge into new or improved products, processes and services for military and dual-use applications. It refers primarily to organisations and activities associated with the defence and dual-use civil-military science, technology, and industrial base", (Cheung, 2014).

Having already defined what will be the object of study, the theories or models that explain how technological innovation is carried out in the field of defence and what are the elements or factors involved in this process are now collected.

One model that explains the factors involved in the ability of countries to produce military technological innovation comes from Schmid (2018), who proposes the *Threat-Capability Theory*. It posits that a state's production of military technology is primarily underpinned by two factors: the state's threat environment and its innovation infrastructure. The concept of the state's threat environment refers to security challenges, both internal and external, as well as the ability of the enemyy to impose negative consequences on the state's leadership.

Cheung is another author who has recently proposed an explanatory theory of a country's defence technological innovation capability (2021: 775-801). The model developed by this author is one of the most complete and focused on military technological innovation available; it also contains the state's threat environment as a determining factor, thus incoporating Schmid's theory into model. This model provides tools for analising the defence innovation system and the results it produces. For these reasons, and because it is one of the most modern models in the military field, Cheung's explanatory model is used in this research.

Cheung's model is based on the study of *national defence innovation systems*, which he defines as a network of organisations and institutions that interactively engage in science, technology and innovation-related activities to advance the development of defence interests and capabilities, especially in relation to strategic, defence and dual-use activities.

This model specifies categories of key factors that are seen as responsible for generating military technological innovation, as well as the relationships between them and a typology of innovation outcomes.

The factors and their categories are summarised in Table 1:

Categorías	***Factores***
Catalizadores	Apoyo de liderazgo de alto nivel; Entorno de amenazas externas; Oportunidades revolucionarias de avances de productos o procesos
Insumos (*Inputs*)	Transferencias de Tecnología Extranjera; Entradas de recursos (asignaciones del presupuesto estatal, inversiones en el mercado de capitales); Capital Humano; Integración Civil-Militar
Instituciones	Planes y Estrategias; Régimen Normativo; Incentivos; Normas de Gobernanza; Relaciones Estado-Mercado
Organizaciones	Corporaciones de Defensa, Organismos Estatales, Entidades Militares; Sistema de Investigación y Desarrollo
Redes y Subsistemas	Proceso de manufactura; Sistema de Adquisición; Redes sociales; Difusión
Contextual	Legado Histórico; Entorno Político Nacional; Nivel de desarrollo, país y tamaño del mercado
Resultados (*Outputs*)	Proceso de producción; Ventas; demanda del usuario final; Comercialización

Table 1. Categorised list of key factors for national defence innovation systems according to Cheung's model.

These categories of factors will be developed further in the analysis section in order to deal in depth with only those aspects that are most relevant to this research.

In addition, Cheung's model defines types of innovation outcomes which he names as follows: duplicative imitation, creative imitation, creative adaptation, crossover innovation, incremental innovation, architectural innovation, component innovation and disruptive innovation. The innovation type that a defence innovation system is capable of producing gives information about its maturity, with the first types being broadly indicative of a limited system and the latter types of an advanced system. The most advanced or top-tier type of innovation, which only countries with the most developed defence innovation systems are capable of producing, is disruptive innovation.

3. Methodology

This research begins with an introduction to the topic, its current relevance and the research question posed. It then presents some theories and models on this field of study in order to provide a framework for the research and tools for analysis and drawing conclusions.

This is followed by a look at the innovation programme that led to the DF-ZF HGV. After assessing some of the key aspects of it, the hierarchical structure of China's defence innovation system is outlined in two diagrams, while the elements involved of the programme's development are pointed out along with details on the role of the various organisations. A timeline of the programme's development is provided to complement this information.

Next, the research is analysed. For this purpose, the categorisation of factors in Cheung's model for defence innovation systems is applied. The analysis is carried out by looking into the outcome types and each factor category of the DF-ZF programme.

Finally, conclusions are drawn with the aim of providing relevant information on China's defence innovation system along with its strengths and weaknesses in relation to its ability to develop military technology.

4. The development the DF-ZF HGV programme

4.1. *China and hypersonic weapons*

Hypersonic is considered to be above Mach 5, i.e. exceeding five times the speed of sound, as shown in figure 2.

Figure 2. Speed ranges according to Mach number.

There are two main types of hypersonic missiles. Hypersonic glide vehicles (HGVs), which have no propulsion of their own and therefore need to be released from high altitude to accelerate using gravity and then glide using aerodynamics; and those with a supersonic combustion ramjet, otherwise known as a *scramjet*. These jets need to be at supersonic speeds to launch, so they need a rocket or supersonic aircraft to release them at these speeds in the atmosphere (not necessarily at high altitudes), and once operational they accelerate the missile up to hypersonic speeds. Hypersonic flight vehicles with a scramjet pose a greater technological challenge than HGVs.

The DF-ZF, being an HGV, does not have a scramjet, but is released at high altitude, above the atmosphere, by a DF-17 ballistic missile[1]. The DF-ZF HGV is capable of reaching and maintaining hypersonic speeds and manoeuvring to alter its trajectory as it loses altitude, as shown at

This system originated in the Cold War era, and consists of establishing in low orbit a weapon system that is capable of slowing down and falling to earth at the desired time, without completing a full orbit, just a fraction of it. This way, it is difficult to know the missile's target until it has begun its descent, the missile can be made to pass close to the poles to make detection more difficult, and it maintains a much lower maximum altitude than the apogee of intercontinental missiles that follow a ballistic trajectory.

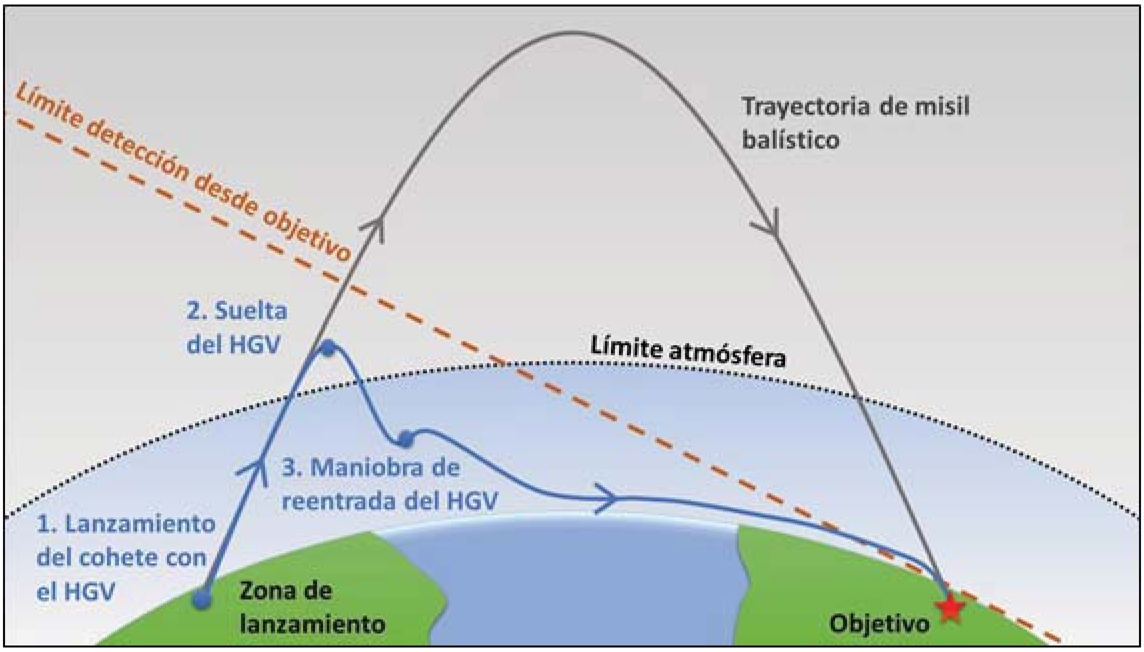

Figure 9. Image of the trajectory followed by an HGV.

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[1] The DF-17 is a medium-range ballistic missile, which can be launched from a mobile platform and has a range of 2,500 km. The DF-ZF HGV is known to have been designed to be launched with this type of missile, but it is not known whether this missile was successful in launching the DF-ZF HGV into orbit or which ballistic missile or rocket carried out the 27 July 2021 launch.

It should be noted that intercontinental ballistic missiles fly at hypersonic speeds for part of their flight. What distinguishes the new generation hypersonic weapon systems is in their ability to maintain these speeds for extended periods of time and to achieve a high degree of manoeuvrability. To achieve such capabilities, the main technical challenges are integral design and materials technologies, testing, navigation and flight validation. (Cai and Xu, 2012).

Hypersonic flight through the atmosphere, even at high altitudes, generates enormous amounts of heat, which can reach 1,000°C. In addition, when returning through the atmosphere, the HGV experiences very intense forces, as well as when performing braking manoeuvres to improve its accuracy or evade interception by defensive systems. Therefore, hypersonic vehicles must have a very strong structure that remains sufficiently light and does not increase its cross-section excessively so as to reduce radar detection. In addition, atmospheric hypersonic flight generates plasma waves that interfere with the communication signals needed to control and correct the HGV's trajectory.

Although considered a cutting-edge technology, controlled hypersonic flight began being a subject of study in the US and USSR in the 1950s. It is estimated that Chinese state laboratories have been studying hypersonic flight as part of their ballistic missile development programme since the 1960s, but that this has remained at a theoretical level due to limited resources (Wood and Cliff, 2020).

Today, the United States has advanced hypersonic scramjet missile projects such as the X-51A, the first tests of which were conducted in 2010. Russia on the other hand has already developed at least two hypersonic weapon systems, the Kinzhal HGV in 2017 and the Avangard scramjet missile in 2019. Russia began testing hypersonic missiles in 2011 (Solem and Montague, 2016: 6-11). In contrast, the first test of the Chinese DF-ZF HGV was conducted in 2014[2] and in 2019 it was declared operational by the Chinese authorities. The DF-ZF HGV development programme has been the shortest of any hypersonic missile programme to date, from the start of flight testing to being operational. In addition, China is developing a hypersonic scramjet-flight vehicle called Xingkong-2(星空,Xīngkōng, "starry sky"). A test flight of more than 400 seconds was conducted in August 2018, and it is expected to be operational for the PLA around 2025 (Hwang and Huh, 2020: 731-743).

A special feature of the DF-ZF HGV development programme was the parallel need for the development of hypersonic wind tunnel facilities. Numerous wind tunnels have been built in China over the past decade, but it is important to highlight JF-12, completed in 2017 and currently the largest and best performing wind tunnel in the world (Wood and Cliff, 2020).

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[2] The Chinese authorities did not release any information on the first DF-ZF test; it was the US Department of Defence that named the detected prototype missile WU-14, for having been launched from a facility in Wuzhai County in 2014. For this reason, information on the DF-ZF can be found under the designation WU-14.

4.2. The programme within China's defence innovation system

Figures 4 and 5 show a simplified organisation chart of China's defence innovation system. They show China's most important organisations, institutions and state-owned enterprises in the field of defence technological innovation, in descending order from the leadership of the CCP and the State Presidency.

The reason there are two organisational charts is because the governmental structure of the country is divided into two, the Party and the State. In China, the CCP is the dominant body and holds political power. However, ministries and institutions are embedded in the hierarchy of the Presidency, under the State Council. On the other hand, the Central Military Commission (CMC), from which the PLA's structure derives, is under the direct aegis of the CCP and its General Secretary. In theory, the State Council also has control over the CMC, but this is merely symbolic.

The breakdown in the structures shown in Figures 4 and 5 depended on the overall degree of need to show the constituent entities. For this reason, among the PLA's branches, only the Strategic Support Force is broken down, to show its high academic research activity as well as its involvement in China's space programme. In the state-dependent structure, the level of ministry, academy or public enterprise is shown, except in the case of the Ministry of Industry and Information Technology, which houses some of the most relevant entities for China's military technological innovation. These figures do not show all of China's ministries, academies, universities, CMC bodies and state-owned enterprises, but only those bodies where collaboration and participation in China's defence innovation system is evident.

Within these structures, the bodies highlighted in orange are those entities directly involved in the DF-ZF HGV development programme and are explained below. Agencies not highlighted in orange are those that are part of China's defence innovation system but have not contributed directly to the DF-ZF programme.

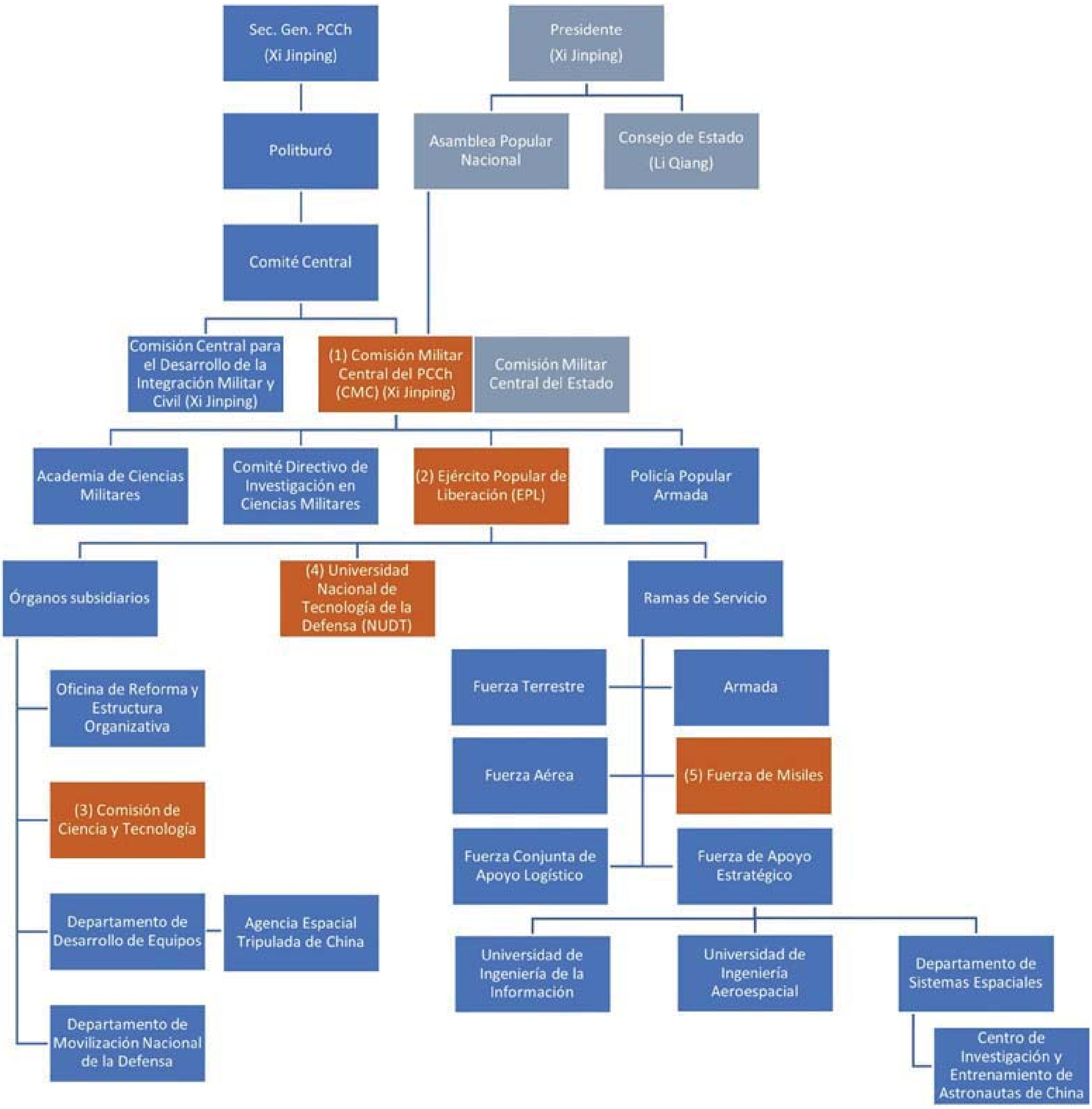

Figure 4. (A) China's defence innovation system, CCP hierarchy.

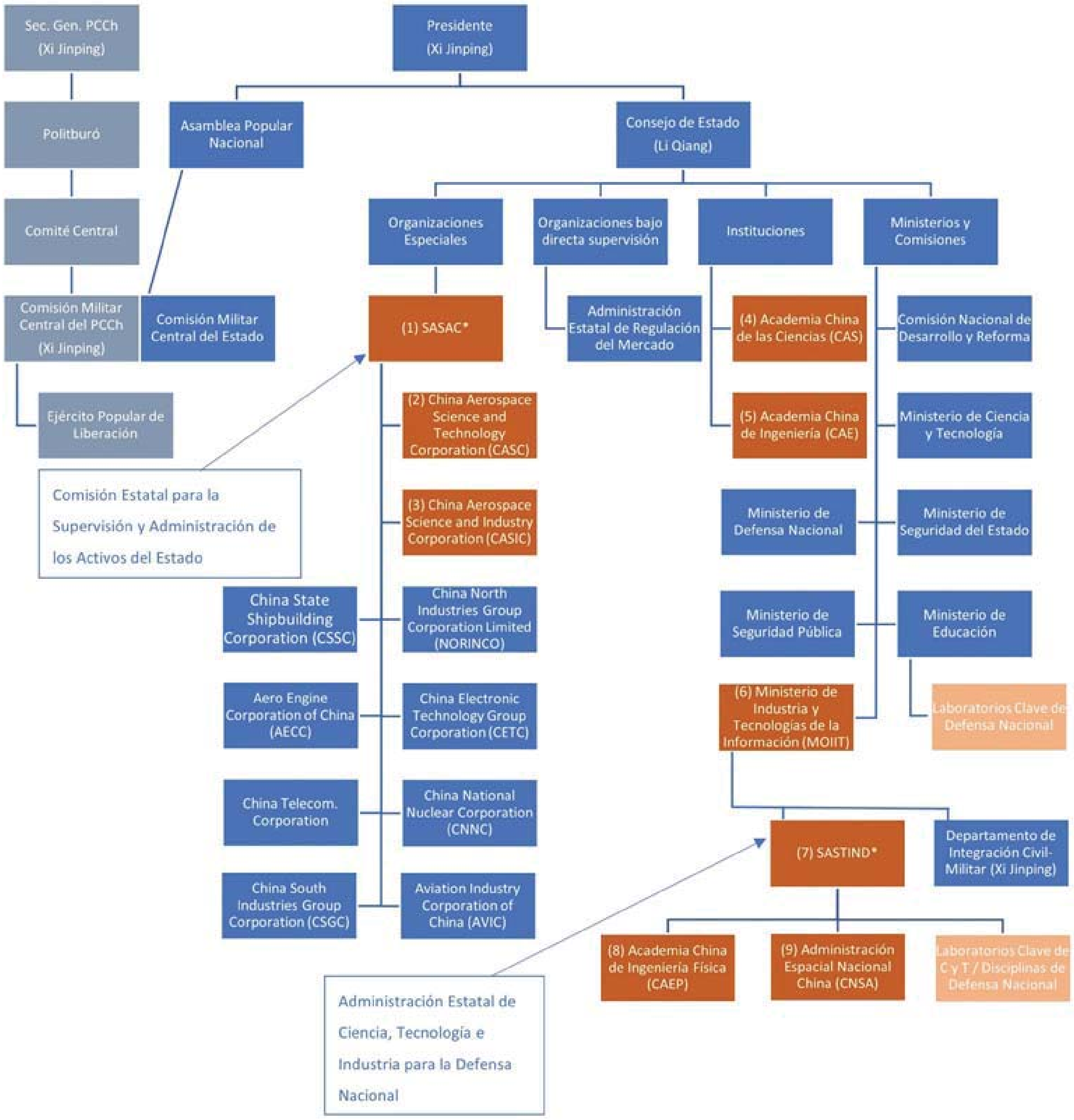

Figure 5. (B) China's defence innovation system, State Presidency hierarchy.

4.2.1. Structure A: CCP hierarchy[3]

1. Central Military Commission of the CCP (CMC) / 中国共产党中央军事委员会

It is the highest national defence organisation of the People's Republic of China and is headed by Xi Jinping.

2. People's Liberation Army (PLA) / 中国人民解放军

The Chinese Armed Forces, broken down into six branches of service.

3. CMC Science and Technology Commission / 中央军事委员会科学技术委员会

It organises and guides military technological innovation by determining long-term priorities. It has supposedly taken over the leadership of the DF-ZF project in the armed forces, as well as the coordination of efforts in the various research fields (Wood and Cliff, 2020).

4. National University of Defense Technology (NUDT) / 国防科技大学

Under the direction of the CMC and the supervision of the Ministry of National Defence and Ministry of Education, the National University has received substantial investments from the army and the state. NUDT's research includes basic research, advanced technology research and defence application research. It was instrumental in the development of the Tianhe-2 supercomputer. Its staff includes members of the Chinese Academy of Sciences and the Chinese Academy of Engineering, as well as personnel from the "Ten Thousand Talents Plan", which is a central government programme to recruit science and technology experts from overseas, mainly from Chinese communities.

In the case of the DF-ZF programme, the College of Aerospace Science and Engineering (CAESE)/ 航天科学与工程学院) at NUDT is said to have been a key academic institute for materials, design and propulsion research. In addition, Wang Zhenguo, deputy chief engineer of China's "Hypersonic Flight Vehicle Science and Technology Project" (高超声速飞行器科技工程), was a student and faculty member for many years (Wood and Cliff, 2020).

5. PLA Rocket Force (PLARF) / 火箭军

This is the PLA branch that operates DF-17 and DF-ZF assets. However, no involvement in the innovation process of the programme was sought beyond the use of the systems. Nor has there been any information on the involvement of other PLA service branches in the programme, including the Strategic Support Force despite the fact that the latter has space-related research institutions.

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[3] As there are cases of different or erroneous translations and even mistranslations between agencies with similar names for the agencies analysed, the names in their most frequent English version as well as their official Mandarin Chinese names are given.

6. Further comments on structure A:

No remarks have been found on any involvement or directives issued by the Central Commission for the Development of Military-Civilian Integration, which has been headed by Xi Jinping himself since its creation in 2017 and which tends to be given a lot of weight as the most important body under the civil-military merger policy.

Nor has there been any involvement detected of other relevant CMC bodies such as the Equipment Development Department, which is said to be responsible for the research, development and procurement of weapons systems for the PLA.

4.2.2. Structure B: State hierarchy

7. State-owned Assets Supervision and Administration Commission (SASAC) / 国务院国有资产监督管理委员会

It manages state-owned enterprises for which it appoints senior executives, approves mergers and securities or asset sales, and drafts regulations.

8. China Aerospace Science and Technology Corporation (CASC) / 中国航天科技集团公司

This is a large state-owned company with a multitude of defence and space subsidiaries and is, in fact, the prime contractor for China's space programme. It was originally founded in 1956 and after numerous reforms became the company it is today at the end of the 1990s. CASC is the company where the DF-ZF HGV and the DF-17 rocket were developed and produced, and where the Xingkong-2 hypersonic scramjet missile prototype is being developed. It is therefore the most important body in China's hypersonic programme. Two entities within CASC are responsible for the DF-ZF programme:

First, the China Academy of Aerospace Aerodynamics (CAAA) / 中国航天空气动力技术研究院,also known as: the China Academy of Aerospace Technology / 11th Academy of CASC / 10th Research Institute of CALT / Near Space Flight Vehicle Research Institute / Beijing Institute of Aerodynamics (BIA) / 701 Institute of CASC.

According to a report for the US-China Economic and Security Review Commission (Stokes and Cheng, 2012), the CAAA was reorganised in 2004 with the mission to focus exclusively on hypersonic vehicles operating in the near-space domain (altitude of between 20 and 100 km). The DF-ZF hypersonic vehicle, as well as the Xingkong-2 prototype, was developed at the CAAA. To this end, the CAAA operates at least three hypersonic wind tunnels that help determine the properties of aircraft travelling at hypersonic speeds. These are FD-02, FD-03 and FD-07. The FD-02 is believed to be capable of generating a simulated range of Mach 3.5 to 8, while the FD-03 and FD-07 can simulate speeds between Mach 5 to 10 and Mach 5 to 12, respectively (Ng, 2022).

The second entity involved is the China Academy of Launch Vehicle Technology (CALT) / 中国运火箭技术研究院,also known as: CASC First Academy.

CALT is China's largest entity involved in the development and manufacture of space launch vehicles and ballistic missile systems. It has developed the Chinese manned space programme's Long March rockets, as well as the DF-17 ballistic missile, capable of carrying the DF-ZF HGV. Through CALT, launch tests of the DF-ZF HGV have been conducted, all from the Jiuquan Satellite Launch Center facility in Wuzhai County, which is also one of the launch sites for the Long March rockets.

9. China Aerospace Science and Industry Corporation (CASIC) / 中国航天科工集团有限公司

CASIC is the sister company of CASC, from which it was spun off in 2001 in order to increase competitiveness and with which it shares the defence and space business. CASIC's involvement in the DF-ZF HGV programme appears to boil down to providing the fuel for the launch rockets through the CASIC Delivery Technology Technical Research Institute (Ng, 2022).

10. Chinese Academy of Sciences (CAS) / 中国科学院

It functions as the national scientific think tank and academic governing body, providing advisory and evaluation services on issues such as the national economy, social development and the progress in science and technology. With hundreds of institutes and tens of thousands of researchers, it is the world's largest research organisation and has been ranked the world's largest research institute by Nature Index.

CAS participated in the DF-ZF programme through its Institute of Mechanics and more specifically from one of its research centres, the State Key Laboratory for High Temperature Gas Dynamics (LHD) / 高温气体动力学国家重点实验室).

According to the Institute's website, the LHD is an open research base dedicated to innovative theoretical research, wind tunnel experiments and digital simulations on high-temperature gas dynamics and aims to investigate hypersonic boundary layer characteristics and aerodynamic configuration theory to solve integrated vehicle optimisation and the flight control of hypersonic vehicles.

Since 2012, the CAS Institute of Mechanics has also had the JF12 hypersonic wind tunnel, the world's best performing tunnel in terms of high temperatures and dwell time. The institute is also developing the JF22, which will further increase the possibilities for hypersonic flight research. According to an article in the Center for Strategic and International Studies journal, the Institute of Mechanics also conducted high-altitude balloon drop tests of different models of hypersonic vehicle profiles in 2018 (Molenda, 2018).

The LHD and its wind tunnel research is considered to have been a key component to the Chinese hypersonic flight vehicle project and thus the DF-ZF HGV development programme. In 1999, Jiang Zonglin, one of China's foremost experts in hypersonic technology, was brought back to China under the "Hundred Talents Programme", and took over as director of the LHD. He is credited with the conception, design and implementation of the JF12 wind tunnel (Wood and Cliff, 2020) (Wood and Cliff, 2020).

11. Chinese Academy of Engineering (CAE) / 中国工程院

It is the national engineering academy of the People's Republic of China and provides consultancy services to the State on major programmes, plans, guidelines and policies. The main contribution of this academy is believed to have been in the development of heat resistant ceramics. In 2017 a research team from the State Key Laboratory for Powder Metallurgy / 粉末冶金国家实验室 at the University of Central South China led by two CAE members announced a breakthrough in ceramic coatings needed for hypersonic vehicles. The team discovered a material composed of zirconium, titanium, boron and carbon capable of withstanding temperatures of up to 3,000 degrees Celsius (Xinhua News Agency, 2017).

12. Ministry of Industry and Information Technology (MOIIT) / 中华人民共和国工业和信息化部

It manages the country's industrial branches and the information industry. It determines industrial planning and promotes the development of major technological equipment and innovation in China's communication and information security sector. Relevant organisations such as SASTIND and the Civil-Military Integration Department (军民结合推进司)report to the MOIIT. The Civil-Military Integration Department is directly chaired by Xi Jinping, highlighting the importance of the Chinese government's civil-military fusion policy, but it is not known whether it has had any involvement in the DF-ZF programme.

13. State Administration of Science, Technology and Industry for National Defence (SASTIND) / 国家国防科技工业局

It is considered one of the most influential bodies in the promotion and application of China's scientific and technological initiatives in the field of defence. Its main responsibilities are nuclear weapons, aerospace technology, aviation, armaments, shipping and electronics. It aims to strengthen the armed forces with modern and advanced equipment.

SASTIND has contributed to the DF-ZF programme, firstly, through programmes to establish national military research laboratories in civilian and military universities; secondly, through the Chinese Academy of Engineering Physics (8); and thirdly, through the Chinese National Space Administration (9).

There are three types of national research laboratories: National Defence Science and Technology Key Laboratories(国防科技重点实验室), National Defence Key Discipline Laboratories(国防重点学科实验室)and the National Defence Key Laboratories(教育部国防重点实验室). SASTIND works to establish defence research laboratories, fund defence-related research areas and facilitate participation in military projects. It is one of the main tools to foster the integration of universities into the defence research system. The first type of the above laboratories is the best funded and most prestigious and the third one is under the Ministry of Education rather than SASTIND, but with identical objectives (Joske, 2019: 8-11).

14. China Academy of Engineering Physics (CAEP) / 中国工程物理研究院

CAEP is the main research and production centre for China's nuclear weapons programme and is overseen by SASTIND and CMC. Regarding the DF-ZF programme, it should be noted that this academy has a hypersonic wind tunnel facility at the Mianyang complex with up to eight large tunnels which is where research for Chinese hypersonic vehicle programmes is believed to have been conducted (Wood and Cliff, 2020). In addition, the DF-ZF HGV is said to have a nuclear warhead-carrying capability, so CAEP's involvement in this area cannot be ruled out.

15. China National Space Administration (CNSA) / 中国国家航天局

This body is responsible for civil space administration and international space cooperation. It is not responsible for the implementation of space programmes, which falls instead to CASC and the China Manned Space Agency (which reports to the CMC).

CASC and CNSA have their origins in a common organisation called China Aerospace Corporation, which split in the late 1990s, giving rise to these two separate entities. This explains why CASC is CNSA's primary contractor, why the DF-ZF programme tests was conducted at CNSA's Jiuquan Satellite Launch Center facility, and why CASC conducted a test in July 2021 that placed the DF-ZF HGV into fractional orbit.

16. Further comments on structure B:

There are some indications that China's defence innovation system has benefited from cooperation with other countries. For example, it is known that in 2017 the University of Central South China announced a collaborative agreement with the University of Manchester in the UK to jointly develop a new type of ceramic coating material for use in hypersonic aircraft and spacecraft (Joske, 2018).

However, it is asserted that, in general, the most relevant patent and publication activity on China's hypersonic flight vehicle programme is concentrated in China's own domestic R&D ecosystem rather than the result of international collaborations (BluePath Labs and Chambers, 2022).

4.3. Programme timeline

The "Hypersonic Flight Vehicle Science and Technology Project" (高超声速飞行器科技工程) was initiated as part of the "National Medium and Long-Term Science and Technology Development Plan (2006-2020)" (国家中长期科学技术发展规划纲要). Just two years earlier, in 2004, a group of senior Chinese aerospace engineers, led by veteran researcher Liu Xingzhou, had made a proposal to the high command on the development of hypersonic flight vehicles. Some reports also state that hypersonic research began to be funded with the establishment of the 863 and 973 programmes, so called ecause they were established in March 1986 and 1997 respectively, well before the official start of the hypersonic aircraft project (Wood and Cliff, 2020).

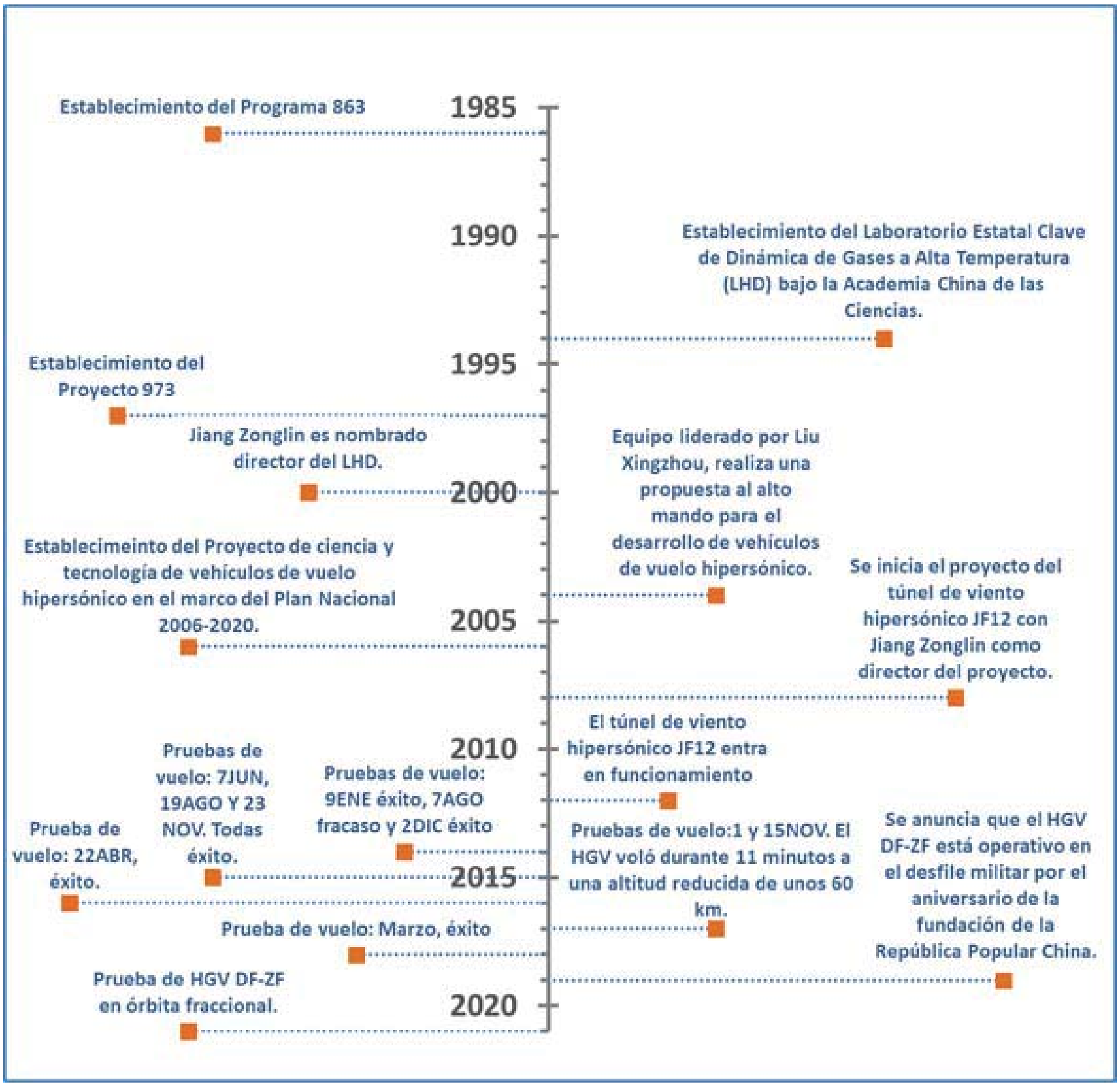


Figure 6. Timeline of the DF-ZF HGV development programme.
Note: Author's own work based on data from China Brief, Washington Free Beacon, China Aerospace Studies Institute and The Diplomat.

5. Analysis based on Cheung's factor model

In order to carry out the analysis of this research, Cheung's model of national defence innovation systems (2021: 775-801) will be used as an analytical tool in this research. This model specifies a set of categories of key factors defined as responsible for the generation of military technological innovation, as well as the relationships between them and the types of innovation outcomes.

The types of innovation outcome of the programme that led to the DF-ZF HGV are analysed, followed by each of the key factor categories. The analysis is limited by the amount of information available for this case study.

5.1. Innovation outcome types

Cheung's model defines an eight-level typology of innovation outcomes, which he calls in the following terms: duplicative imitation, creative imitation, creative adaptation, crossover innovation, incremental innovation, architectural innovation, component innovation and disruptive innovation. The type of innovation that a defence innovation system is capable of producing is indicative of its maturity, with the first types being broadly indicative of a more limited system and the latter indicative of a more advanced system.

The DF-ZF programme has resulted in the development of a ballistic missile system with a hypersonic glide vehicle (HGV), which has been successfully tested and put into operation. Moreover, only five years separated the start of the first flight tests of this programme on 9 January 2014 and the 1 October 2019 announcement that the DF-ZF HGV was operational, making it the shortest known hypersonic missile programme. The programme also left behind a range of cutting-edge infrastructure in China for hypersonic technology research such as wind tunnels.

The technology developed for this weapon system consisted of an increase in technique and knowledge in several scientific areas, in particular: heat management, aerodynamics, G-force resistance and navigation. It ought to be recalled that many of the ballistic missiles previously developed by China experienced hypersonic conditions for parts of their flight, so these areas of research are not new. What distinguishes DF-ZF HGV is its ability to maintain hypersonic speeds for extended periods of time and to have a high degree of manoeuvrability and control, which has required significant scientific advances.

The DF-ZF, being an HGV, does not have a scramjet, which would be a somewhat groundbreaking development, as scramjets are a major challenge and a novelty among modern weapon systems. China is making progress in the development of hypersonic scramjet vehicles, but today the hypersonic weapon system China has in operation is of the less complex type, the HGV.

For these reasons, it can be concluded that the DF-ZF programme presents two types of innovation outcomes as defined by Cheung. They are incremental innovation and component innovation.

For Cheung, incremental innovation, fifth on the scale of eight, is the upgrading or limited improvement of existing locally developed systems and processes. Incremental innovation can also be the gradual upgrading of a system through the introduction of improved sub-systems. By contrast, component innovation, the seventh on the scale of eight, involves the development of new component technology that can be incorporated into the existing system architecture. Component innovation emphasises hard innovation capabilities, such as advanced R&D facilities, a cadre of experienced scientists and engineers, and large- investments.

The DF-ZF programme would be close to but falls short of the eighth and the most advanced level of innovation, disruptive innovation. For Cheung, this requires major breakthroughs in both technology and new component architecture and can only be achieved by countries with world-class research and development capabilities and personnel coupled with large financial resources and a willingness to take the risk of failure.

It is therefore considered that in the case of the DF-ZF programme, China's defence innovation system has demonstrated a high capacity for innovative results, achieving innovation of a complexity level of 5-7 out of 8.

5.2. Catalytic factors

Catalytic factors are top-level leadership support, external threat environment and revolutionary product or process breakthrough opportunities. According to Cheung, catalysts are the spark that ignites the most disruptive innovation.

These factors are mainly external to the defence innovation system and would be the subject of a whole investigation in their own right, so only some of the most relevant aspects for this case study will be outlined.

There is no doubt that technological advances in the hypersonic field in China enjoy high-level Chinese support. This is evidenced by the continuous approval of high-level technology development plans and programmes and the allocation of large sums of money, which are reflected in the large number of participating organisations and companies involved, as well as the developed infrastructure of world-class wind tunnels.

In terms of the external threat environment, the installation of anti-missile systems in areas close to China such as South Korea, Japan and the island of Guam has led China to perceive threats to its interests (Solem and Montague, 2016: 6-11). These facts, according to Cheung's model and Schmid's Threat-Capability Theory, have served as a catalyst for China's defence innovation system in the development of hypersonic technologies. The DF-17 hypersonic missile is designed to strike enemy bases and fleets in the Western Pacific, according to a US Department of Defense report on security and the Chinese military to US Congress (Office of the Secretary of Defense, 2022).

In terms of breakthrough opportunities for innovation, the closest in this respect can be considered to have been the advances in wind tunnel performance that have enabled vigorous research and advancement in the science around hypersonic technologies.

The catalytic factors have therefore been optimal for China's defence innovation system to develop the DF-ZF programme.

5.3. Input factors

The input factors are foreign technology transfers, resource inputs (state budget allocations, capital market investments), human capital and civil-military integration. They are therefore the contributions that flow into the defence innovation system.

In the case of the DF-ZF programme, foreign technology transfer made a marginal contribution to the programme, with only one known international university collaboration, between the University of South Central China and the University of Manchester in the UK. The programme was clearly funded by public money and implemented by public insititutions. Following Cheung's model, the big missing element in this project was private equity investment. In the case of the DF-ZF programme, China's defence innovation system, at least at a high level, had little of the dynamism and efficiency that private sector involvement brings. It is not known how much public money was invested in the project, but the public money was effective and the time spent on the DF-ZF programme was relatively short.

In terms of human capital, it has become clear that Chinese talent recruitment programmes abroad have been important, for example, in the research staff of NUDT, CAS and more specifically in the recruitment of the expert Jiang Zonglin to head the State Key Laboratory of High Temperature Gas Dynamics, as well as the JF12 hypersonic wind tunnel development project. On the one hand, this shows that there is a need in China to recruit experts who have been trained outside the country, but on the other hand, it also shows that there are effective strategies in China to bring back this talent.

It is not known whether there were any initiatives for civil-military integration within the DF-ZF programme. However, there is evidence of the involvement of some defence research laboratories from civilian universities, such as the State Key Laboratory for Powder Metallurgy; the the involvement of the NUDT, which collaborates on dual-use programmes such as supercomputers; and the involvement of CALT, which produces the Long March rockets for China's manned space programme as well as the DF-17 ballistic missiles that carry the DF-ZF HGVs. The laboratories set up by SASTIND and the Ministry of Education are one of the main tools for including universities and different civilian agencies in the military sphere (Joske, 2019: 8-11).

According to Cheung's theoretical framework, developing defence innovation systems are strongly characterised by technology transfer and factors that emphasise the importance of the role of the state, such as government agencies. In contrast, an advanced defence innovation system is characterised by bottom-up factors such as the primacy of the market, incentives that support risk-taking, intellectual property protection and organisations that promote market and research activities such as companies and universities.

China's national defence system in the case of the DF-ZF programme does not fit either of these two definitions, as neither technology transfers nor a private market push played a major role. China's national defence system has been successful in developing this programme despite not having significant private company participation and relying almost entirely on public organisations. Moreover, they have been able to generate innovation without the need for high technology transfer inputs.

5.4. Institutional factors

Institutional factors are plans and strategies, regulatory regimes, incentives, governance rules and state-market relations.

China's defence innovation system is very much determined by China's politics. The CCP exercises control over the system, dictates priorities and distributes the means to carry them out. To this end, the Chinese authorities are launching both temporary and open-ended technology development programmes. The DF-ZF programme is a clear result of the National Medium- and Long-Term Science and Technology Development Plan (2006-2020) and the resulting Hypersonic Flight Vehicle Science and Technology Project.

In this case, state-market relations do not seem to have had much influence and there is a clear dominance of the government's top-down initiative.

5.5. Organisational factors

Organisations are the main actors within the defence innovation system and are formal structures that are deliberately created with an explicit purpose. They include companies, govenrments, universities, research institutes and a varied range of other organisational entities. Private individuals may also be involved.

As shown in Figures 4 and 5, the organisations involved in the DF-ZF programme were government agencies in different fields. It is noteworthy that both CMC and State Council bodies were involved in the development of this programme, which shows coordination between the two hierarchies.

Within the PLA, the involvement of coordinating bodies and academic bodies can be observed, but not that of the Missile Force, which is responsible for operating the system. Under the State Council, there is the involvement of coordinating bodies, ministries, multiple academic bodies, research laboratories and the main entity in charge of developing the DF-ZF HGV, the large state-owned company CASC.

It is worth noting that within the CASC, the CAAA research body was formed in 2004; specialising in near-space hypersonic vehicles, reflecting the importance given to this field by Chinese authorities and the flexibility of state-owned companies in terms of reorganization.

Once again, the big missing actor in this picture is the private sector, at least at a high level of involvement. It is striking that despite this shortcoming, considered by authors such as Cheung to be one of the main elements of an advanced defence innovation system, the Chinese programme has achieved a very high level of success.

5.6. Networks and sub-systems

Social, professional or virtual networks allow actors, especially individuals, the means to connect with each other within and beyond defence innovation systems, both nationally and internationally. Networks provide effective channels for sharing information, often more quickly and comprehensively than traditional institutional links, and help overcome barriers to innovation such as rigid compartmentalisation.

By its nature, it is very difficult to access information about the internal workings of public departments and the ways in which they interact with other public entities in the context of China's defence innovation system.

Based on the contributions that can be observed from various entities to the DF-ZF programme, it can be seen that there is a scientific communication and collaboration network that is sufficiently effective in bringing together efforts in the same field and creating synergies for the development of defence technology. Significantly, collaboration was achieved from PLA entities under the CMC and state-owned enterprises, academia and ministries under the State Council, which defies the existence of compartmentalisation in China's defence innovation system. In addition, the success of some Chinese state programmes such as overseas talent recruitment and the establishment of research laboratories with defence-related fields in universities and other civilian public bodies can be noted.

5.8. Contextual factors

This category covers the set of different factors that influence and shape the overall defence innovation environment. Contextual elements that exert a strong influence include historical legacies, the domestic political environment, the level of development, and the size of the country and its markets. Contextual factors, like catalysts, are external to the defence innovation system and could be studied extensively. For the purposes of the analysis of this case study, only some of the most relevant aspects will be highlighted.

In the introductory section of this research, some words from Xi Jinping's speeches at the last two CCP congresses in 2017 and 2022 were laid out. Xi Jinping clearly pointed to the central role of the CCP in the country's politics as the distinguishing feature of the Chinese political system and as an element of superiority over others. Furthermore, it can be seen that the importance of improving the country's military capabilities through technology has been maintained from 2017 to 2022 to form part of the "strategic tasks for building a modern socialist country in all respects".

Some other relevant contextual data on China's defence environment is its defence budget, which has grown along with the size of its economy. Despite having kept its defence spending at a few fractions below 2 % of its GDP, over the past decades China's defence budget has grown to be the second largest in the world, although apparently still far from the much higher US spending, according to Stockholm International Peace Research Institute (SIPRI) databases.

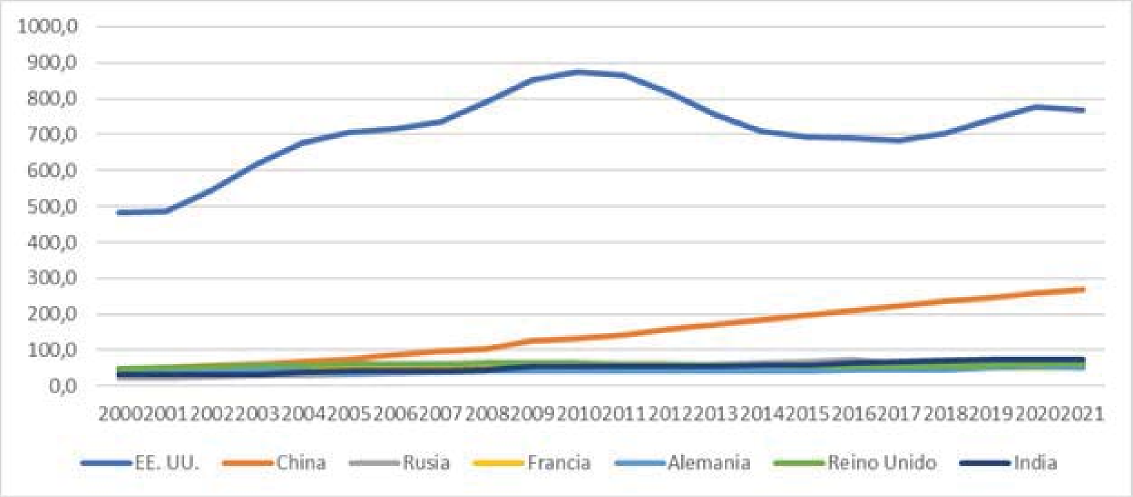
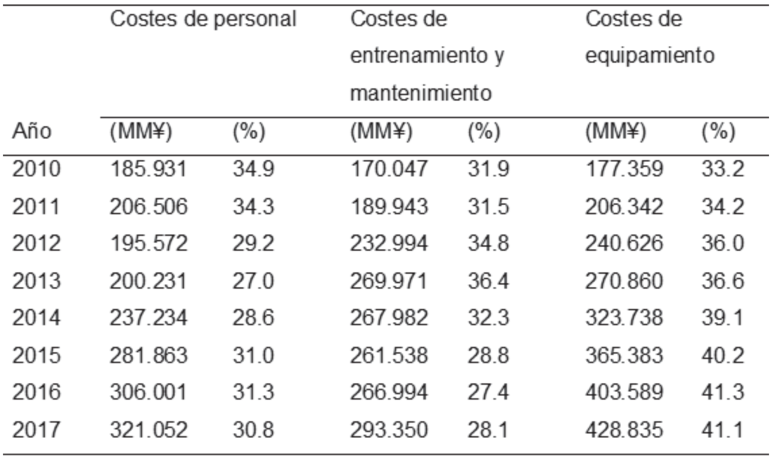


Figure 7. Military expenditure for the period 2000-2021 in billions of dollars based on the value of the dollar in 2020.
Note: SIPRI makes its own estimates of national military spending that do not always agree with officially published data, as is the case for China. Data from www.sipri.org
Nota. SIPRI hace sus propias estimaciones del gasto militar nacional que no siempre concuerda con los datos publicados oficialmente, como es en el caso de China. Datos de: www.sipri.org

While, in simple monetary terms, China's military spending appears much lower than that of the United States, under the Purchasing Power Parity (PPP) exchange factor comparison, which takes into account the difference in operational and personnel costs in each country, Peter Robertson (2019) of Western Australia University, stated that China's budget in 2019 was about 75 % of that of the US.

One of the few official publications of China's defence budget breakdown comes from the 2019 China Defence White Paper, which revealed how previous years' budgets were broken down into three main categories: personnel costs, training and maintenance costs, and equipment costs.



	Costes de personal		Costes de entrenamiento y mantenimiento		Costes de equipamiento	
Año	(MM¥)	(%)	(MM¥)	(%)	(MM¥)	(%)
2010	185.931	34.9	170.047	31.9	177.359	33.2
2011	206.506	34.3	189.943	31.5	206.342	34.2
2012	195.572	29.2	232.994	34.8	240.626	36.0
2013	200.231	27.0	269.971	36.4	270.860	36.6
2014	237.234	28.6	267.982	32.3	323.738	39.1
2015	281.863	31.0	261.538	28.8	365.383	40.2
2016	306.001	31.3	266.994	27.4	403.589	41.3
2017	321.052	30.8	293.350	28.1	428.835	41.1

Table 2. Official publication of the breakdown of China's defence expenditure (2010-2017) (in billions of RMB). Note. Source: Information Office of the State Council of the People's Republic of China (2019). China's National Defense in the New Era.

Significantly, the equipment item is the only item that has increased as a proportion of the budget, rising by almost 8 % in 7 years. This seems to indicate that the Chinese authorities' priority to better equip their armed forces is materialising and is reflected in budget allocations.

5.8. *Output factors*

The output factors are production process, sales, end-user demand and marketing. This category is responsible for determining the nature of the products and processes coming out of the defence innovation system.

In the case of the DF-ZF programme, the sole user is the PLA Missile Force, which would use it as a weapon system to provide the Armed Forces with the capability to penetrate defensive systems.

It cannot be excluded that this system could later be commercialised or that some of the technologies developed within this project could be used in other weapon systems for commercial purposes, even though these would not fall within the programme's main objectives. According to SIPRI data, Chinese-made missile exports accounted for 29 %, 12 % and 13 % of the total value of China's military exports in 2000, 2010 and 2020, respectively.

6. Conclusions

The analysis and conclusions of this research are subject to the information available and collected for this case study. The lack of transparency in this area was an obstacle to research, but also an opportunity to generate original ideas.

An analysis of the DF-ZF HGV development programme shows that both catalytic and contextual factors, which are external to China's defence innovation system, were very favourable to the development of the project. Some of the key factors that have stimulated innovation have been the strong support at the highest political level, the perception of external threats from China that this programme addresses, and technological advances in the construction of wind tunnels that have allowed the hypersonic research to be accelerated.

In addition, the political backdrop, in general and the military context, in particular, have also been propitious for the proper development of the programme. Xi Jinping declared in 2022 that advancing the country's military capabilities through technology was one of the "strategic tasks for building a modern socialist country in all respects". Moreover, it is fact that Chinese military spending in recent years has increased robustly, keeping pace with China's economic growth, and that this spending is increasingly focused on weapons systems.

The DF-ZF programme was therefore conducted under external conditions that were very favourable to China's defence innovation system.

However, the results achieved in the DF-ZF programme do not amount to breakthroughs in technology, but they do represent incremental and component breakthroughs. According to Cheung's model, this programme would have reached an outcome-type level of 5-7 out of 8, and would be just one step away from achieving breakthrough innovation, the most complex and advanced type.

The development of the DF-ZF HGV has required significant advances in science and technology in areas such as the resilience of materials, aerodynamics and navigation. However, the DF-ZF HGV does not represent a technology milestone that announces that China is leaving other powers behind. Potential future developments in hypersonic scramjet flight vehicles would represent a higher type of outcome than that achieved by this programme, due to its greater complexity and novelty.

The timeline of the programme is also a relevant element. The DF-ZF HGV development programme, from start of flight testing to operational use, was the shortest of the hypersonic missile system development programmes. This is a positive sign for the capability of China's defence innovation system. It will be important to see how quickly China can bring the Xingkong-2, for which flight testing began in 2018, up to speed.

In the DF-ZF programme, the contributions of technology transfers, typical of a developing system, were not significant, but neither was there a high participation of private companies, typical of an advanced system, according to Cheung's model. The Chinese system is different, but it is undoubtedly capable of achieving innovation results. The analysis in this case study shows that the general approach to China's defence innovation system has been a model of selective state mobilisation complemented by dynamic tools. In this system, the Chinese authorities mobilise and concentrate resources in a select group of sectors and agencies through a top-down state allocation process, usually based on a series of technology development plans; but this model is complemented by system-performance tools such as civil-military fusion, talent acquisition and research programmes and policies.

The most important weakness observed in China's defence innovation system in the case of the DF-ZF HGV development programme has been the limited high-level involvement of the private sector, which according to Cheung's model should be a major element.

In contrast, other factors have been observed that are dynamic tools which could be considered strengths of China's defence innovation system. These are the civil-military fusion policies, state programmes for attracting talent from abroad and the programmes for establishing military research laboratories in public universities or other civilian organisations that are carried out by SASTIND.

In the DF-ZF programme, the important contributions of the military university NUDT, the CAS Institute of Mechanics, the state company CASC and the relations with the CNSA space programme, all of which are involved in civil-military dual-use technology, stand out as examples of civil-military fusion. Also the fact that the main hypersonic wind tunnels were located in military and civilian research organisations such as the CAAA of the CASC, the Institute of Mechanics of the CAS or the CAEP of the SASTIND.

From the state talent recruitment programmes it has been identified that NUDT has benefited from the "Ten Thousand Talents Plan" and the LHD Laboratory of the CAS Institute of Mechanics from the "One Hundred Talents Programme". The recruitment of the expert Jiang Zonglin through this programme to lead the LHD Laboratory and the development of the JF-12 wind tunnel deserves being highlighted.

Some of the most prominent laboratories in the DF-ZF programme with military research links were the LHD Laboratory at the CAS Institute of Mechanics and the State Key Laboratory of Powder Metallurgy at the University of Central South China.

Within the country's complex and extensive public sector fabric, China's defence innovation system has been able to overcome compartmentalisation and achieve inter-agency collaboration to generate synergies between state-owned enterprises, national academies,

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