An Evolutionary Game Simulation of a Composite Subsidy Policy to Promote Military-Civilian Integration: A National System of Innovation With Chinese Characteristics

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ABSTRACT Collaborative innovation involving military and civilian actors is a key component of National Systems of Innovation. It is an approach that is explicitly promoted in China under the name of Military-Civilian Integration. To more effectively promote Military-Civilian Integration, it is necessary to study the impact of government subsidies on enterprise-level behavior. The research reported in this paper analyzes a composite subsidy policy’s influence on the cooperative innovation behavior of military and civilian enterprises with game theory. First, during the early stage of development, an R&D subsidy can stimulate firms to invest in technological innovation, but it harms the long-term and stable development of civil-military cooperation by encouraging free-riding behaviors. Second, as military-civilian integration continues and deepens, the input-output rate of the R&D will increase, and this makes the role of tax subsidies increasingly relevant. Third, the composite application of scale and tax subsidies will be most effective in reinforcing innovation during the Industrialization Stage. Fourth, further simulations show an apparent heterogeneity in the responses of the military enterprise and the civilian enterprise to the three kinds of subsidy that we have considered. Civilian enterprises are more sensitive to subsidies, while military enterprises are more sensitive to technology spillovers. Therefore, the government should build a military-civilian integration platform to share resources in ways that maintain security confidence and improve the R&D input-output rate. The government should strengthen confidentiality management, training, and risk prevention and control measures for military-civilian integration projects, to reduce the risk of technology spillover.

INDEX TERMS Collaborative innovation, evolutionary game, military-civilian integration, subsidy policy.

I. INTRODUCTION
Military-civilian integration is a key national development strategy of China, in more detail, military-civilian integration combines the modernization of national defense and its forces into the economic and social development system. The principal development tools of military-civilian integration are sponsorship of scientific and technological innovation, procurement, development of new enterprises, and industrial integration (supply chains). Among these, the sponsorship of scientific and technological innovation is the most foundational premise and driving force of military-civilian integration.

By way of example, technical cooperation to produce the C919 domestic large passenger aircraft one of the special projects to develop large aircraft in China, is a typical
military-civilian integration project. The C919 is a medium and short-range commercial trunk aircraft with independent intellectual property rights. The project to develop the C919 has achieved 102 critical technological breakthroughs, such as improvements in thrust reverser design and in active control technology. In the development process of the C919, a large aircraft technology innovation system centered on COMAC has gradually emerged. This new innovation system has engaged 36 colleges and universities to participate in developing large aircraft projects. It has also engaged 22 provinces and cities in China and more than 200 military and civilian enterprises to work on the development of large aircraft [1].

Such major technological projects, of which C919 is just one example, are to be found in aerospace, high-end equipment manufacturing, new materials, advanced energy, ocean engineering, and in other fields as well. These come with a parallel burden of organization, which grows more complex as individual organizations are blended into an innovation system. From this observation springs a further task of great significance. Namely, an obligation to study and clarify the managerial, organizational and operational issues that govern the success of innovation systems including those which arise out of military-civilian integration.

China’s military-civilian integration innovation system is gradually taking shape, and military-civilian cooperation is gradually increasing. However, from the perspective of China’s practical experience, there is still an inevitable gulf of understanding between the military and civilians, and the interests of military and civilian parties are not aligned [2]. Systems for sharing technology and information between military and civilian enterprises have not yet fully matured in China. In order to break down institutional barriers and to promote the development of military-civilian integration and the scientific and technological innovation that will spring from such integration, China’s central and local governments have promulgated a series of policies and measures to produce weapons and equipment, personnel training, socialized support for the armed forces, and mobilization of national defense in ways that involve civilian-military integration.

Military-civilian integration has been a policy of the centre since the eighteenth session of the Communist Party of China [3]. Since that date, many local governments of China, such as Hunan [3] and Sichuan [4], have also issued measures to the same end. These provide financial and policy support to enterprises engaged in military-civilian integration, in accordance with the specific conditions of their region. Through analysis of the policies of various provinces and cities [5], [6], we have found that the primary policy instruments adopted in China at the provincial and city levels mostly consist of a range of incentives, such as admission qualification awards, pre-research funds, subsidies for the improvement of production conditions, tax rebates, and the creation of industrial parks. However, can military-civilian integration and its associated scientific and technological innovation system be formed purely through incentives: that is, as long as enough subsidies are given? Only a more careful analysis can answer that question.

Incentives imply local autonomy; on the other hand, every innovation system, including a military-civilian integration system, is a system: it has a certain degree of integration and complexity whereby actions in one part affect another [7].

There are also fundamental differences between the goals of the military and the civilian sides of a military-civilian system, which need to be acknowledged. The military has a strong interest in maintaining control over access to its core technologies at a fundamental, strategic level, and its tolerance for technology spillover is consequently limited. On the other hand, the civilian side is highly sensitive to the costs of R&D, the costs of production, and other costs it faces.

In addition, a single subsidy policy cannot adequately meet the different stages of technological innovation, which generally have different needs and face different obstacles. However, more diversified assistance mechanisms can do more to promote the full chain of innovation, both in general terms and in the context of military-civilian integration [8].

Therefore, it is of great theoretical and practical significance that we should analyze the conditions of formation and incentive policy needs of innovation systems in general, and those involving military-civilian integration in particular. The contributions of this article to that end are presented as follows. To begin with, most of the existing literature only considers the broad impact of subsidy policies on innovation and pays less attention to the role of diversified or composite policies.

This paper agrees with the main conclusion of the existing literature, namely that government subsidies have promoted the development of military technologies and their eventual civilian spinoffs. However, the research which we have undertaken, and which we report in this paper, shows that the government should adopt different subsidy policies at different stages of the military-civilian innovation process, in order to promote more effective collaboration. When it comes to military-civilian integration, we find that most of the existing literature is founded on symmetrical models which do not take into account the heterogeneity of the military and the civilian sides of a system of innovation that involves both.

The present study shows that the respective responses to subsidy policies shown by the military and the civilian sides of such a joint innovation system are indeed different. Assistance and incentives should take account of these differences. At the same time, while giving appropriate subsidies, the government should also take appropriate measures to improve the institutional density of the military-civilian innovation ecosystem, to build trust, and to otherwise enhance the willingness of military and civilian enterprises to collaborate.

The remainder of the present paper is introduced as follows: Section II reviews the most important current literature on military-civilian integration as a system of innovation. Section III establishes what we call the cooperative innovation model. In that model, we locate the different risk preferences of military and civilian organizations in the context
of an evolutionary game. The cooperative innovation model is explored further in Section IV. In this section, the equilibrium of the evolutionary game and its stability are analyzed. Section V discusses the influence of different subsidies and their combinations on the evolution and stability of the joint decision-making of military and civilian organizations. Finally, the simulation analysis undertaken in Section VI yields a more intuitive reflection of the heterogeneity of military and civil organizations engaged in cooperative innovation. Our conclusions are furnished in the final section.

II. LITERATURE REVIEW
A. MILITARY-CIVILIAN INTEGRATION INNOVATION SYSTEM
All industrial nations have at least some historical experience of the integration of the military with the civilian industrial economy and the emergence of a collaborative innovation system. As early as 1950, China put forward the concept of “military and civilian dual-use,” which was the earliest prototype of the concept of military-civilian integration in China; this early version of present policy was intended to enhance the efficiency of the defense industry system, to achieve more comprehensive utilization of resources, and last but not least to tap the modernizing potential of military technologies for the wider industrial economy and society as a whole. In 1987, The British economist Christopher Freeman [9] provides a handy outline of the concept of the “National System of Innovation” in his paper, emphasizing that national economic policies play a crucial role in promoting technological innovation and the formation of the innovation system at the level of each country, or in a cluster of countries if the nations involved are small and adjacent, as in parts of Europe.

Research on military-civilian integration has attracted extensive attention from scholars. Domestic scholars have analyzed and discussed the Chinese civil-military innovation system from several perspectives. Among these scholars, at the beginning of the 21st century, Peng [10], You [11], and others pointed out that building an innovative military-civilian industrial system was an urgent requirement for China’s modernization in the face of the world’s ongoing scientific and technological revolution. Subsequently, scholars have conducted in-depth research on China’s military-civilian innovation system. An article by Wang focuses on collaborative innovation under oligopoly, using a game theory approach [12]. That author’s research results have proved that the formation of an innovation system helps enterprises to increase investment in innovation. He and Hou [13] constructed a model featuring four kinds of defense science and technology innovation organizations engaged in military-civilian integration. Their research emphasizes the role of two especially crucial types of organization in the Chinese military-civilian innovation system. In China, state-owned military enterprises have considerable financial and technical strength and have become the core agencies of national defense technology innovation. At the same time, commercial high-tech enterprises have flexible mechanisms, strong motivation to innovate, and a solid ability to apply advanced scientific and technological achievements. These commercial enterprises can produce many dual-use scientific and technological products and can provide technical and production support for state-owned military enterprises.

Based on the above research on military-civilian integration as an innovation system, this paper classifies the subjects of innovation into military and civilian, and models their collaboration and of the effect of policy instruments applied by the government in the hope of producing greater coordination and direction of efforts than would otherwise arise.

B. SUBSIDY MECHANISM
In the military-civilian innovation system, the distribution of interests and goals among the decision-making participants, such as the government, military research organizations, civilian technology enterprises, and scientific research organizations, has a direct bearing on the degree of enthusiasm of each participant when it comes to a joint project of technological innovation. As noted, the coordinating system needs to be nuanced enough to take account of this diversity.

We note, first, that there is no doubt that government support has actively promoted technological innovation through cooperation between military and civilian institutions [14]. By the end of the Cold War, research by the American scholar Mowery [15] already showed that defense R&D investment had had a significant impact on the industrial innovativeness of the civilian sector in OECD countries. Second, many scholars have since discussed the role of policy-driven subsidies on scientific and technological innovation. Mao and Xu [16] systematically evaluated the micro-level effect of government subsidies on new product innovation by enterprises. Their research shows that even moderate subsidies can significantly stimulate new product innovation. Chen and Zhou [17] divided the goals of military-civilian integration innovation into development-oriented and research-oriented classes, and analyzed the impact of government subsidies on the performance of innovation participants according to their different risk preferences and expectations of benefits. Liu et al. [18] took government subsidies as the regulating mechanism for conflicts and alliances between foreign-funded R&D and independent innovation participants. These research results show that although government subsidies have a particularly positive effect on scientific and technological cooperation in innovation, it is still necessary to consider the strength of the policy instrument, the fields to which the policy instrument is applied, and the different characteristics of the organizations to which the policy instrument is applied.

In recent years, the development of evolutionary game theory has laid a foundation for studying the process of group decision-making in evolutionary terms. Evolutionary game theory is a dynamic method for studying group evolution; it takes evolutionary dynamics under frequency constrained selection as its research object. Due to the hypothesis of bounded rationality, it is often impossible for both sides of the
game to achieve equilibrium, that is to say a set of outcomes for each participant that none can improve upon, in the process of one game. The players need to constantly iterate and improve their strategies and to play repeated games [19].

In a key contribution to this field, Smith [20] proposed the concept of Evolutionary-Stable Strategy (ESS) and concluded that a stable strategy is not necessarily unique. Taylor and Jonker [21] proposed “replication dynamics” that mirror the evolution of biological traits and behavioral characteristics. Evolutionary game theory scholars have also labored to construct a two-party and three-party cooperation mechanisms by which to address the stability of outcomes. Along with many other scholars, Fang et al. [22], An and Chen [23], Zhao et al. [24], Zhao and Huang [25], Xu et al. [26], and Xu [27] et al. have used evolutionary game theory to construct game models and have used these models to make in-depth analyses of the evolutionary stability of the cooperation mechanism in the context of military-civilian integration as an innovation system or, as we might say in this context, an innovation ecosystem.

Researchers working in this new field all argue that factors such as the integrative and transformative capabilities of technological R&D, and the cost and profit distribution ratios of collaborative innovation, will directly affect the evolutionary direction of the participants’ behavior in the course of joint military-civilian innovation. The work done to date lays a foundation for the work in this paper, in which we use evolutionary game theory to study the decision-making of scientific and technological innovators engaged in military-civilian integration.

However, most scholars working on military-civilian integration from a standpoint of evolutionary game theory have, to date, only considered the impact of a single subsidy policy on the innovation system. They rarely consider the impact of more varied subsidies and incentive policies at different stages of the innovation process. In addition, the military and civilian actors have generally been regarded as similar enterprises in terms of their response to policy instruments. Such symmetrical game models seldom reflect the divergence of military and civilian preferences when it comes to technological risks and cost risks.

From our analysis of the literature above, it seems clear that scholars in several fields have emphasized the importance of building a military-civilian integration system, and of the crucial role of national economic policies in fine-tuning and steering the innovation ecosystem that has thus come into being.

In this paper, we model military enterprises and civilian enterprises as the two subjects of the military-civilian innovation system (which is thus reduced to an system, of two parts), establish a revenue model based on the different risk preferences of the two parts, and analyze the impact of three subsidies and their combined application on the evolutionary results and stability of the system.

The key element of research innovation claimed for this paper is that we have considered the different risk preferences of the military and civilian organizations in our revenue model. To reiterate, military enterprises are more sensitive to technology spillover risk, to losing control of technology and the pace of technological progress at a basic level, while private enterprises are more sensitive to the risk of cost and delivery-time blowouts in R&D. In addition, this paper considers the impact of the three subsidies at different stages of the joint military-civilian innovation process, and on the subsequent evolution results of cooperative decision-making. This will provide a basis upon which the government may build more targeted subsidy policies.

III. EVOLUTIONARY GAME MODEL

A. SIMULATION ASSUMPTION

Before describing our evolutionary game model, we first put forward five underlying assumptions.

Assumption 1: We suppose that there are two parties, representing all types of military and civilian organizations respectively, in our model of the integrated military-civilian innovation ecosystem. We denote the military part as M and the civilian part as C. The military and civilian parts, which we refer to henceforth as the enterprises, will continuously learn and adjust their respective strategies on a basis of bounded rationality until they reach equilibrium. We assumed that the strategy set of both enterprises, M and C, is \{Positive Cooperation, Passive Cooperation\}.

Enterprises that choose Positive Cooperation will actively invest and industrialize their scientific and technological achievements to maximize benefits. Enterprises that choose Passive Cooperation are unwilling to carry out substantive cooperation due to their risk aversion in the face of the uncertainty of cooperation results, do not carry out R&D investment, and only expect to enjoy the benefits of the other party’s investment or government subsidies. Here, we denote the probability of Positive Cooperation by the military enterprise (M) as \(x\), and the probability of Passive Cooperation by the military enterprise as \((1 - x)\). Similarly, the probability of Positive Cooperation by the civilian enterprise (C) is \(y\), and the probability of Passive Cooperative by the civilian enterprise is \((1 - y)\).

Assumption 2: In our model, we assume that the military and civilian enterprises are already in receipt of benefits based on the original technology before collaborative technological innovation cooperation. We call these primary benefits. The primary benefits of the military enterprise are \(B_m\), and that of the civilian enterprise are \(B_c\). Assuming that both enterprises are ordinary taxpayers, they should pay tax according to the income generated, at a tax rate of \(\tau\).

Assumption 3: The player that adopts the Positive Cooperative strategy will actively invest R&D funds for scientific research activities. We denote the R&D input of the military enterprise as \(I_m\) and that of the civilian enterprise as \(I_c\). We denote the input-output rate of R&D as \(\theta\).

A technological spillover effect will occur in the course of collaborative technological innovation between military and
civil enterprises. The government’s industrial policies will impact the technology spillover level [28]. D’ Aspremont and Jacquemin [29] proposed that technology spillovers would reduce the unit production costs of both parties in R&D cooperation. In their specification, the spillover effect of one party is to lower the unit production cost of the other party. In addition, other scholars have proposed that technology spillovers will either positively or passively affect R&D investment and innovation performance [30]. As compared with these papers, we consider the effect of Technology spillover in asymmetric terms of the lowering of production costs for both enterprises and of the technology spillover risk to the military enterprise. We assume that the closer the cooperation between the two enterprises, the higher the technology spillover coefficient. In addition to reducing the unit production cost of both the military and civilian enterprises, technology spillover will increase the spillover risk perceived by the military enterprise. We denote the technology spillover coefficient as $\beta$. Through the R&D investment of military enterprises and technology spillovers of the civilian enterprise, the military enterprise’s production processes and efficiency will be improved so that its production costs will be reduced by $\theta(I_m + \beta I_c)$. Likewise, the production cost of the civilian enterprise is reduced by $\theta(I_c + \beta I_m)$.

The transformation of technological innovations arrived at by military-civilian collaboration into practical, industrial progress is also a critical part of the process. The scale of industrial implementation is an essential indicator of success in this final stage of the process. We denote the scale of industrial implementation as $\gamma$, such that $\gamma \geq 1$. Although the greater the scale the greater the return, the market price will also decrease with increasing scale. Here, we refer to Chen’s conclusion. He considered that for any enterprise, there is an optimal company boundary. When the scale reaches a certain level, the operation and management of the enterprise become incredibly complex, which often requires better management and organization, and the savings brought by economies of scale have a smaller and smaller impact[31]. Therefore, we quantify the return index on the industrial-implementation scale, which we term the industrialization scale, by $\ln \gamma$. The revenue generated from research and development is $\theta(I_m + \beta I_c) \ln \gamma$, $\theta(I_c + \beta I_m) \ln \gamma$.

Assumption 4: Yin et al. [32] notes that China has introduced many policies to promote the transformation of green technology into new industries operating at scale. These policies are targeted at technological innovation, the sales of manufacturing enterprises, and the purchases of consumers. Nie et al. [33] introduced subsidy intensity into an income model and proved that a subsidy improves collaborative green innovation. In military-civilian integration, the government will implement supportive policies such as taxation and scale-up subsidies for military and civilian enterprises. As compared with the earlier work of Nie et al. [33], we introduce three kinds of subsidies for different stages of technical cooperation: tax rebates, R&D subsidies, and scale-up subsidies for industrialization. We assume that the government gives tax rebates to the military and civilian enterprises carrying out technical cooperation, and we denote the tax rebate rates for the military and civilian enterprises as $\tau_m$ and $\tau_c$, respectively. We assume that governments only give R&D subsidies to the military and civilian enterprises in proportion to the enterprise’s own R&D investment in the R&D stage (“pro rata”) and we denote the R&D subsidy rate as $S$. To promote industrialization at scale, governments will also give subsidies to the military and civilian enterprises. We denote the industrialization scale-up subsidy rate as $P$.

Assumption 5: The military and civilian enterprises have different risk preferences in technical cooperation. The military enterprise pursues not only military benefits or strives to take the lead in military technology innovation and security but also shows high sensitivity to the risk of technology spillover. The civilian enterprise has keen insight into the market and the ability to explore the market. However, if the civilian enterprise fails in innovation or is overtaken by competitors, all its R&D investments will become sunk costs. Therefore, the civilian enterprise is sensitive to the risks of R&D investment.

As compared to the civilian enterprise, the military enterprises are more vulnerable to forms of harm caused by loss of control over its technology, and so its cooperation strategy and R&D investment are more readily affected by the degree of technology spillover. We used $\beta I_m$ to represent the military enterprise’s R&D investment risk cost. On the other hand, we use $I_c/\theta$ to represent the R&D investment of the civilian enterprise, for it is more sensitive to cost.

B. MODELS

On the basis of the above five assumptions, we then established a payoff matrix for both sides of the game, as shown in Table 1.

When both enterprises adopt a Positive Cooperation strategy, they will each actively invest in R&D. The income of each enterprise will consist of after-tax income and subsidy income, minus risk cost. The risk cost of the civilian enterprise is R&D investment risk, and the risk cost of the military enterprise is the technology spillover risk. Both enterprises will receive tax subsidies for engaging in technical cooperation and, as such, participating in military-civilian integration.

When one enterprise cooperates positively (Positive Cooperation) and the other enterprise cooperates passively (Passive Cooperation), the one which cooperates positively will not get the technology spillover of the other enterprise but will bear its own risk cost. The passively cooperating enterprise will share the technology spillovers of the other enterprise without bearing its own risk cost. Once more, both enterprises will receive tax subsidies for engaging in technical cooperation and, as such, participating in military-civilian integration.

When both enterprises choose Passive Cooperation, the benefits to each enterprise will consist only of their basic after-tax incomes. They will not be eligible for subsidies, but they will also escape their respective risk costs.
Based on the payoff matrix of the evolutionary game established in Table 1, the expected return to the military enterprise when it chooses the Positive Cooperation strategy is as follows:

\[
U_{m1} = y \left\{ (1 - \tau + \tau_m) \left[ B_m - I_m + \theta (I_m + \beta I_c) \ln \gamma \right] + (S - \beta) I_m + \gamma P \right\} + (1 - y) \left\{ (1 - \tau + \tau_m) \left( B_m - I_m + \theta I_m \ln \gamma \right) + (S - \beta) I_m + \gamma P \right\}
\]

When the military enterprise chooses the Passive Cooperation strategy, its expected income is as follows:

\[
U_{m2} = y \left\{ (1 - \tau + \tau_c) \left[ B_c - I_c + \theta (I_c + \beta I_m) \ln \gamma \right] + (S - 1/\theta) I_c + \gamma P_c \right\} + (1 - y) \left\{ (1 - \tau + \tau_c) \left( B_c - I_c + \theta I_m \ln \gamma \right) + (S - 1/\theta) I_c + \gamma P_c \right\}
\]

When the civilian enterprise chooses the Cooperative Innovation strategy, its expected income is then given as follows:

\[
\bar{U}_m = x U_{m1} + (1 - x) U_{m2}
\]

The replicated dynamic equation of the military enterprise is as follows:

\[
F(x) = dx/dt = x \left\{ U_{m1} - \bar{U}_m \right\} = x (1 - x) (U_{m1} - U_{m2})
\]

\[
= x (1 - x) \left\{ y \left( -\tau_m B_m - \gamma P \right) + (1 - \tau + \tau_m) \left( \theta I_m \ln \gamma - I_m \right) + S I_m + \gamma P - \beta I_m + \tau_mB_m \right\}
\]

(1)

The replicated dynamic equation of the civilian enterprise is as follows:

\[
C(y) = dy/dt = y \left\{ Uc1 - \bar{U}c \right\} = y (1 - y) \left\{ Uc1 - Uc2 \right\}
\]

\[
= y (1 - y) \left\{ \left( -\tau_c B_c - \gamma P \right) + (1 - \tau + \tau_c) \left( \theta I_c \ln \gamma - I_c \right) + (S - 1/\theta) I_c + \gamma P + \tau c B_c \right\}
\]

(2)

To obtain the equilibrium solution for the joint evolution of the military and civilian enterprises, let \( F(x) = 0 \) and \( C(y) = 0 \), equations which should be solved jointly. Therefore, there are five equilibrium points of the system: \((0, 0), (0, 1), (1, 0), (1, 1), \) and \((x_0, y_0)\). Here,

\[
x_0 = \left\{ \left( (1 - \tau + \tau_c) (\theta \ln \gamma - 1) + S - 1/\theta \right) \times I_c + \tau_r B_c + \gamma P \right\} / (\tau_r B_c + \gamma P),
\]

\[
y_0 = \left\{ \left( (1 - \tau + \tau_m) (\theta \ln \gamma - 1) + S - \beta \right) \times I_m + \tau_mB_m + \gamma P \right\} / (\tau_mB_m + \gamma P).
\]

### IV. ANALYSIS OF THE STABLE STRATEGIES

Equipped with the above assumptions and the replicated dynamic system, we can analyze the stable strategy of each
enterprise based on the stability theorem of differential equations. The equilibrium point will be asymptotic stability when the derivative of $F(x)$ is less than 0. The same is true for $y$. Furthermore, we establish the Jacobian matrix of the system, analyze local stability to verify whether the strategy combination formed by the two parties is an ESS, and analyze the effect of the subsidies on the strategy selection in detail.

A. THE ASYMPTOTIC STABILITY STRATEGY OF THE MILITARY ENTERPRISE

If $F(x) = 0$ and $F'(x) < 0$, then $x$ is an asymptotically stable strategy of the military enterprise. Thus, we can obtain the derivative of Equation (1) as follows:

$$F'(x) = (1 - 2x) \cdot [y(-\tau_mB_m - yP) + (1 - \tau + \tau_m) \times (\theta I_m \ln \gamma - I_m) + SI_m + \gamma P - \beta I_m + \tau_mB_m].$$

(3)

For convenience of expression, we define $A = (1 - \tau + \tau_m) (\theta \ln \gamma - 1) I_m + (S - \beta) I_m + \gamma P + \tau_mB_m$ and $C = -\tau_mB_m - \gamma P$, then $F'(x) = x (1 - 2x) (yC + A)$. The influence of the relationship between $A$ and $C$ upon the stability strategy is discussed under the following three cases.

Case 1: $A > 0$, $C < 0$, and $A + C = (1 - \tau + \tau_m) (\theta \ln \gamma - 1) I_m + (S - \beta) I_m > 0$.

Then,

$$(1 - \tau + \tau_m) (\theta \ln \gamma - 1) I_m + SI_m > \beta I_m.$$  

(4)

Equation (4) indicates that the R&D income of the military enterprise after receiving tax subsidies and R&D subsidies is higher than the risk cost caused by technology spillover. In this case, $yC + A > 0$. Thus, $\forall y \in [0, 1], \exists F'(x) < 0$. Then $x = 0$ is the stable point. That is, Positive Cooperation is the dominant strategy of the military enterprise.

Case 2: $A > 0$, $C < 0$, and $A + C = (1 - \tau + \tau_m) (\theta \ln \gamma - 1) I_m + (S - \beta) I_m < 0$.

Then,

$$(1 - \tau + \tau_m) (\theta \ln \gamma - 1) I_m + SI_m < \beta I_m.$$  

(5)

Equation (5) indicates that the R&D income of the military enterprise after receiving tax subsidies and R&D subsidies is lower than the risk cost caused by technology spillover. In this case, $yC + A < 0$, then $x = 0$ is the stable point of the military enterprise, while if $yC + A > 0$, then $x = 1$ is its stable point.

Case 3: $A < 0$, $C < 0$, and $A + C = (1 - \tau + \tau_m) (\theta I_m \ln \gamma - I_m) + (S - \beta) I_m < 0$.

Then,

$$(1 - \tau + \tau_m) (\theta \ln \gamma - 1) I_m + SI_m < \beta I_m.$$  

(6)

Equation (6) indicates that the R&D income of the military enterprise, after receiving tax subsidies and R&D subsidies, is lower than the risk cost caused by technology spillover. In this case, $yC + A < 0$. Thus, $\forall y \in [0, 1], \exists F'(x) < 0$. Then $x = 0$ is the stable point. That is, Passive Cooperation is the dominant strategy of the military enterprise.

B. THE ASYMPTOTIC STABILITY STRATEGY OF THE CIVILIAN ENTERPRISE

If $C(y) = 0$ and $C'(y) < 0$, then $y$ is the asymptotic stability strategy of the civilian enterprise. We can obtain the derivative of Equation (2) as follows.

$$C'(y) = (1 - 2y) \times [(\theta \ln \gamma - 1) I_c + (S - 1/\theta) I_c + \gamma P + \tau_mB_c]$$

(7)

Equation (8) means that when the R&D income of the civilian enterprise, after receiving tax subsidies and R&D subsidies, is higher than the risk cost caused by the R&D input cost, then $Dx + B > 0$. Thus $\forall x \in [0, 1], \exists F'(x) < 0$. It follows that $y = 1$ is the evolutionary-stable point of the civilian enterprise. That is, Positive Cooperation is the asymptotic stability strategy of the civilian enterprise.

Case 2: $B > 0$, $D < 0$, and $B + D = (1 - \tau + \tau_c) (\theta I_c \ln \gamma - I_c) + SI_c - I_c/\theta > 0$.

Then,

$$(1 - \tau + \tau_c) (\theta \ln \gamma - 1) I_c + SI_c < I_c/\theta.$$  

(8)

Equation (9) indicates that the R&D income of the civilian enterprise, after receiving tax subsidies and R&D subsidies, is lower than the risk cost caused by the R&D input cost. At this condition, if $Dx + B > 0$, then $y = 1$ is the asymptotic stable point, while if $Dx + B < 0$, $y = 0$ is the asymptotic stable point.

Case 3: $B < 0$, $D < 0$, and $B + D = (1 - \tau + \tau_c) (\theta \ln \gamma - 1) I_c + (S - 1/\theta) I_c < 0$.

Then,

$$(1 - \tau + \tau_c) (\theta \ln \gamma - 1) I_c + SI_c < I_c/\theta.$$  

(9)

Equation (10) indicates that the R&D income of civilian enterprises, after receiving tax subsidies and R&D subsidies, is lower than the risk cost caused by the R&D input cost. In this case, if $Dx + B < 0$, then $\forall x \in [0, 1], \exists C'(y) < 0$. It follows that $y = 0$ is the asymptotic stable point.
determine the probability of a stable equilibrium at (1,1). That will be the stable strategy for both enterprises.

Enterprises falls within the polygon EOGH, Passive Cooperation when the strategy combination of the military and civil enterprises. On the other hand, enterprises falls within the polygon EFGH, Positive Cooperation when the strategy combination of the military and civil enterprises.

Based on the above stability analysis. According to Fig. 1, (1,1) are the two asymptotic stable points of the system, (0,1) and (0,0) are the two unstable points, and (x0, y0) is the saddle point.

Equation (11) indicates that the smaller S1 is, the greater the probability of Positive Cooperation is, and the larger S1 is, the greater is the probability of Passive Cooperation. Moreover, the area of S1 is affected by various government subsidy rates, the technology spillover coefficient, the input-output rate of R&D, industrialization scale, and other parameters. Under the circumstance of different technology spillover levels and the input-output rate of R&D, different support policies will play crucial roles in the evolution of the joint decision-making of both enterprises.

| Table 2. Results of local stability analysis. |

| The balance(x,y) | dtJ symbol | trJ symbol | Result |
|------------------|------------|------------|--------|
| (0,0)            | +          | –          | ESS    |
| (0,1)            | +          | +          | unstable |
| (1,0)            | +          | +          | unstable |
| (1,1)            | –          | 0          | Saddle point |

C. ANALYSIS OF LOCAL STABILITY

We analyze the local stability of the five stable equilibrium points using the Jacobian matrix in accordance with Hirshleifer’s method.

Let

\[ D = \begin{bmatrix} F_x & F_y \\ C_x & C_y \end{bmatrix} \]

then, the Jacobian determinant is W, and the Jacobian’s trace is Q, as shown at the bottom of the page. The local stability analysis results of the differential equation and Jacobian matrix are presented in Table 2. Table 2 shows that (0,0) and (1,1) are the two asymptotic stable points of the system, (0,1) and (1,0) are the two unstable points, and (x0, y0) is the saddle point.

Fig. 1 shows the phase diagram of the evolutionary game based on the above stability analysis. According to Fig. 1, when the strategy combination of the military and civil enterprises falls within the polygon EFGH, Positive Cooperation will be a stable strategy for both enterprises. On the other hand, when the strategy combination of the military and civil enterprises falls within the polygon EOGH, Passive Cooperation will be the stable strategy for both enterprises.

Therefore, the areas of the polygons EFGH and EOGH will determine the probability of a stable equilibrium at (1,1). That is, of Positive Cooperation by both enterprises. The area of the polygon EOGH can be described as follows:

\[ S_1 = EOGH = \frac{(x_0 + y_0)}{2} \]

\[ = \frac{[(1 - x + x_c)(\theta \ln \gamma - 1) + S - 1]}{2} \]

\[ \times \beta_m \times B_m + \gamma P] / [2 (\tau_m B_m + \gamma P)] \]

\[ + [(1 - x + x_m)(\theta \ln \gamma - 1) + S - \beta] \]

\[ \times \beta_m \times B_m + \gamma P] / [2 (\tau_m B_m + \gamma P)] \]  

\[ (11) \]

W = (1 − 2x) [y (−τ_m B − γ P) + (1 − γ − τ_m) (θ I_m ln γ − I_m) + S I_m + γ P − β I_m + τ_m B_m]

\[ \times (1 - 2y) (x (−τ_B c − γ P) + (1 - γ - τ_c) (θ I_c ln γ − I_c) + S I_c + γ P − I_c/θ + τ_B C) \]

\[ - (x (1 - x) (−γ P - τ_m B_m) \times y (1 - y) (−τ_B c − γ P)] \]

Q = (1 − 2x) [y (−τ_m B − γ P) + (1 − γ − τ_m) (θ ln γ - 1) I_m + (S - β) I_m + γ P + τ_m B_m]

\[ + (1 - 2y) [x (−τ_B c − γ P) + (1 - γ - τ_c) (θ ln γ - 1) I_c + (S - 1/θ) I_c + γ P + τ_B C] \]

Fig. 1. Phase diagram of the evolutionary game.
policies proposed in Assumption 4 in Part III, as based on Equation (11).

A. SINGLE POLICY

1) R&D SUBSIDY RATE

We assume that governments only give R&D subsidies to the military and civilian enterprises in proportion to the enterprise’s own R&D investment in the R&D stage (“pro rata”). S is the R&D subsidy rate. The effect of the R&D subsidy rate on the military-civilian cooperation is analyzed below, in terms of the change of the area S1 with S.

In this case, \( P = 0, \tau_c = 0, \text{and } \tau_m = 0. \) That is

\[
S'_1 = \lim_{P \to 0} \left( \frac{I_c + I_m}{2P} \right) > 0
\]  

(12)

According to Equation (12), when the R&D subsidy rate S increases, the area of S1 will increase accordingly, and the probability of Positive Cooperation between the military and civilian enterprises will decrease. The income matrix in Table 2 shows that R&D subsidies will undoubtedly increase the level of R&D investment by the enterprise. However, in the process of military-civilian R&D cooperation, an enterprise engaged in Passive Cooperation will obtain technology spillover benefits due to the other party’s input even if it does not invest. However, if the R&D subsidy rate S increases, an enterprise pursuing Passive Cooperation will obtain more technology spillover benefits. In contrast, the enterprise pursuing Positive Cooperation will face more significant investment or technology spillover risks. The initiative of the enterprise pursuing Positive Cooperation strategy will be damaged and transformed into Passive Cooperation, thus leading to a joint Passive Cooperation equilibrium. For that reason, relying solely on R&D subsidies to encourage collaborative innovation will trigger enterprises to choose the passive strategy, a form of free-riding, which will render collaborative innovation unsustainable.

2) THE INDUSTRIAL SCALE SUBSIDY RATE

We assume that governments only give industrial scale subsidies to the military and civilian enterprises in proportion according to the actual scale of industrialization (i.e., production) achieved. Here, P represents the rate of the industrial scale subsidy. The effect of the rate of the industrial scale subsidy on the trend of civil-military collaborative innovation is analyzed in accordance with the change of the area S1 with P.

In this case, \( S = 0, \tau_m = 0, \text{and } \tau_c = 0. \) That is

\[
S'_1 = \{-I_m \left[ (\theta \ln \gamma - 1) (1 - \tau) - \beta \right] \\
- I_c \left[ (\theta \ln \gamma - 1) (1 - \tau) - 1/\theta \right] \}/2P^2
\]  

(13)

In Equation (13), if the following conditions are met, then \( S'_1 > 0. \)

\[
(\theta \ln \gamma - 1) (1 - \tau) - \beta < 0
\]  

(14)

\[
(\theta \ln \gamma - 1) (1 - \tau) - 1/\theta < 0
\]  

(15)

According to the income matrix in Table 2, Equations (14) and (15) can be extended as follows:

\[
(B_m + I_m \theta \ln \gamma - I_m) (1 - \tau) - B_m (1 - \tau) < \beta I_m
\]  

(16)

\[
(B_c + I_c \theta \ln \gamma - I_c) (1 - \tau) - B_c (1 - \tau) < I_c/\theta
\]  

(17)

In Equation (16), the after-tax return of the R&D investment of the military enterprise is lower than its technical spillover risk cost. In Equation (17), the after-tax return of the R&D investment of the civilian enterprise is lower than its R&D investment risk cost. Under these two conditions, the area of S1 will increase with the expansion of the industrialization scale subsidy rate P and the probability of positive cooperation between the military and civilian enterprises will decrease. Even if an increase in the scale subsidy rate can encourage enterprises to expand their industrialization scale, the civilian enterprise will face relatively large investment risks if the R&D input-output rate is low. The military enterprise will also face relatively large technology spillover risks once the technology spillover reaches a certain level.

When the after-tax income of the R&D investment of both enterprises is insufficient to cover the technology spillover risk or the R&D investment risk, the respective desire of each enterprise for R&D investment will decline. In this situation, each enterprise will reduce R&D investment to manage its respective risk and this will lead to the gradual evolution of the game into a mutual Passive Cooperation equilibrium. Therefore, increasing the scale subsidy rate P at this time will harm cooperation. On the other hand, Equations (13), (16), and (17) show that the growth of P will decrease \( |S'_1| \). That means that there is a countervailing tendency, also associated with increase in the scale subsidy rate P, which favors Positive Cooperation.

In Equation (13), if the following conditions are met, \( S'_1 < 0: \)

\[
(\theta \ln \gamma - 1) (1 - \tau) - \beta > 0
\]  

(18)

\[
(\theta \ln \gamma - 1) (1 - \tau) - 1/\theta > 0
\]  

(19)

According to the income matrix in Table 2, we extend Equations (18) and (19) as follows:

\[
(B_m + I_m \theta \ln \gamma - I_m) (1 - \tau) - B_m (1 - \tau) > \beta I_m
\]  

(20)

\[
(B_c + I_c \theta \ln \gamma - I_c) (1 - \tau) - B_c (1 - \tau) > I_c/\theta
\]  

(21)

In Equation (20), the after-tax return of the R&D investment of the military enterprise is higher than its technical risk cost caused by technology spillover. In Equation (21), the after-tax return of the R&D investment of the civilian enterprise is higher than its risk cost of R&D investment. Under these two conditions, the area of S1 will decrease as the scale subsidy rate P increases, which means that the probability of Positive Cooperation between the military and the civilian enterprises will increase. In this circumstance, the increase of the industrialization scale subsidy rate P will promote the expansion of the scale of the military and civilian enterprises, thereby generating more profits and reinforcing Positive Cooperation. Thus, in this instance, increasing the scale subsidy rate P

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has a positive impact on both enterprises’ choice of Positive Cooperation. In addition, according to Equations (13), (20), and (21), an increase in $P$ will decrease $|S'_1|$. That is, the increasing rate of the evolution trend of the cooperation toward the Positive Cooperative stabilization strategy will decrease. Thus, excessive increase of the industrialization scale subsidy rate will decrease the supporting effect of policy subsidy on collaborative innovation.

3) TAX SUBSIDY RATE

It is assumed that governments also actively manage the level of tax rebates, which we will call tax subsidies for consistency with the other types of subsidy, given to the military and civilian enterprises participating in military and civilian cooperative innovation.

Here, $\tau_m$ represents the tax subsidy rate given to the military enterprise participating in cooperative innovation, while $\tau_c$ represents the tax subsidy rate given to the civilian enterprise participating in cooperative innovation. The influence of the tax subsidy rate on the trend of civil-military cooperation is analyzed in accordance with the change of the area $S_1$ with $\tau_m$ and $\tau_c$.

(1) The tax subsidy rate for civilian enterprises.

In this case, $S = 0$, $P = 0$, $\tau_m = 0$. That is

$$S'_1 = -(I_c (\ln \gamma - 1) (1 - \tau) - 1/\theta) / 2B_c \tau_c^2 \quad (22)$$

In Equation (22), if the following conditions are met, then $S'_1 > 0$.

$$(\ln \gamma - 1) (1 - \tau) - 1/\theta < 0 \quad (23)$$

According to the income matrix in Table 2, we extend Equation (23) as follows:

$$(B_c + I_c \theta \ln \gamma - I_c) (1 - \tau) - B_c (1 - \tau) > I_c / \theta \quad (24)$$

In Equation (24), the after-tax income of the civilian enterprise is lower than its risk cost of R&D investment. The area $S_1$ will increase as the tax subsidy rate $\tau_c$ increases, and the possibility that the strategy of both sides tends to a stable regime of mutual Positive Cooperation will therefore reduce. It can be seen from the income matrix in Table 2 that increasing the tax subsidy rate $\tau_c$ will apparently reduce the tax pressure on the civilian enterprise and improve its income. However, when the input-output rate $\theta$ of R&D of both parties is low or the industrialization scale is small, the income of the civilian enterprise is not enough to resist the risk cost of R&D investment even if the tax subsidy rate $\tau_c$ increases. What this means is that, if the tax subsidy rate $\tau_c$ continues to increase, the dependence of the civilian enterprise on subsidies will increase, the R&D investment will reduce to mitigate risks, and eventually the civilian strategy will evolve into Passive Cooperation, with a similar consequence for the entire game.

In Equation (22), if the following conditions are met, $S'_1 < 0$:

$$(\ln \gamma - 1) (1 - \tau) - 1/\theta > 0 \quad (25)$$

In accordance with the income matrix, we extend Equation (22) as follows:

$$(B_c + I_c \theta \ln \gamma - I_c) (1 - \tau) - B_c (1 - \tau) > I_c / \theta \quad (26)$$

In Equation (26), the after-tax income generated by R&D investment in the civilian enterprise is higher than the risk cost of R&D investment. In this circumstance, the area $S_1$ decreases as the tax subsidy rate $\tau_c$ increases, and the probability of Positive Cooperation between the military and civilian enterprises will increase. Clearly, under this condition, an increase in the tax subsidy rate $\tau_c$ has reinforces Positive Cooperation on both sides of the game. In addition, an increase in $\tau_c$ will reduce $|S'_1|$, which means that the probability of Positive Cooperation decisions between military and civilian enterprises will decrease. Therefore, with the substantial increase in tax subsidy, the effect of which on promoting active cooperation between the two sides will reduce, and the effectiveness of the policy will reduce.

(2) The tax subsidy rate for military enterprises.

In this case, $S = 0$, $P = 0$, $\tau_c = 0$. That is

$$S'_1 = -(I_m [(\theta \ln \gamma - 1) (1 - \tau) - \beta]) / (2B_m \tau_m^2) \quad (27)$$

In Equation (27), if the following conditions are met, $S'_1 > 0$:

$$(\theta \ln \gamma - 1) (1 - \tau) - \beta < 0 \quad (28)$$

In accordance with the income matrix in Table 2, we extend Equation (28) as follows:

$$(B_m + I_m \theta \ln \gamma - I_m) (1 - \tau) - B_m (1 - \tau) < \beta I_m \quad (29)$$

In Equation (29), the after-tax return of the military enterprise’s R&D investment is lower than its cost of technology spillover risk. In this circumstance, the area $S_1$ will increase as the tax subsidy rate $\tau_m$ increases, and the probability of Positive Cooperation between the military and civilian enterprises will decrease. On the surface, increasing the tax subsidy rate $\tau_m$ will reduce the tax pressure on the military enterprise and improve its income. However, when both enterprises’ R&D input-output rate $\theta$ is low, or the industrialization scale is small, the military enterprise’s income after R&D investment will still be insufficient to cover the risk cost of technology spillover even if the tax subsidy rate increases. As noted, the military enterprise is susceptible to technology spillover. When its income is low, the military enterprise will reduce R&D investment to reduce its spillover risk, and its strategy will thus evolve into Passive Cooperation.

In Formula (27), if the following conditions are met, $S'_1 < 0$:

$$(\theta \ln \gamma - 1) (1 - \tau) - \beta > 0 \quad (30)$$

In accordance with the income matrix in Table 2, we extend Equation (30) as follows:

$$(B_m + I_m \theta \ln \gamma - I_m) (1 - \tau) - B_m (1 - \tau) > \beta I_m \quad (31)$$
In Equation (31), the after-tax return of the military enterprise’s R&D investment is higher than the cost of its technology spillover risk. In this circumstance, the area \( S_1 \) will decrease as the tax subsidy rate \( \tau_m \) increases, and the probability of Positive Cooperation between the military and civilian enterprises will increase. In this case, an increase in the tax subsidy will reinforce Positive Cooperation strategies on both sides of the game.

### B. COMPOSITE POLICY

Single subsidy policies have limitations when applied across different scientific and technological innovation stages. This paper will therefore explore the effect of subsidy policies tailored to promote military-civilian cooperation at different stages, an approach which we call a composite subsidy policy. It is important to note that the words single and composite apply to the subsidy policy and its implementation (its ‘regime’), and not to the number of actual subsidies. The composite subsidy policy and its regime is composite over time and across stages in the innovation process. The fact that several different sorts of subsidies have already been discussed is a separate matter. If those subsidies do not vary over time, we speak of a single subsidy policy and regime even though there are several types of subsidy.

#### 1) R&D SUBSIDY RATE

We assume the government has decided to apply a composite subsidy policy to the military and civilian enterprises. We will analyze the effect of the R&D subsidy rates in the composite subsidy policy upon the evolutionary trend of military-civilian collaborative innovation as follows:

\[
S_1'(S) = \frac{I_m}{2} (B_m \tau_m + \gamma P) + I_c/2 (B_c \tau_c + \gamma P) > 0
\]

In Equation (32), when \( S_1' > 0 \), an increase of \( S \) will make \( S_1 \) increase, and the probability of Positive Cooperation between military and civilian enterprises will decrease. This result is consistent with the analysis results in a1. Undoubtedly, increasing the subsidy rate of R&D investment will promote R&D investment in the military and civilian enterprises when it comes to independent projects. However, the greater the R&D investment risk or technology spillover risk in R&D cooperation, the more likely it is that the military and civilian enterprises will reduce their investment and turn to Passive Cooperation. Therefore, an increase in \( S \) undermines the Positive Cooperation of the military and civilian enterprises.

Furthermore, we observe that when the government embarks upon a composite subsidy policy, an increase in \( P \), \( \tau_m \), and \( \tau_c \) reduces the growth rate of the probability of Passive Cooperation between the military and civilian enterprises. Therefore, in the early stage of military-civilian collaboration in innovation, when an organization to manage the system of innovation has not yet been formed, R&D subsidies can incentivize Positive Cooperation. However, from the perspective of long-term evolution, after collaborative innovation organizations have been formed, R&D subsidies will not play a positive role. Governments should gradually diminish R&D subsidies at that stage and consider increasing tax subsidies, industrialization scale subsidies, and other policies relevant to the shift from R&D to industrial production.

#### 2) INDUSTRIALIZATION SCALE SUBSIDIES

We will analyze the effect of the industrialization scale subsidy in the composite subsidy policy, in accordance with the change of the area of \( S_1 \) with \( P \).

\[
S_1'(P) = -\left\{\gamma I_m [S - \beta + (\theta \ln \gamma - 1) (1 - \tau + \tau_m)]\right\}/(B_m \tau_m + \gamma P)^2
+ \left\{I_c [S - 1/\theta + (\theta \ln \gamma - 1) (1 - \tau + \tau_c)]\right\}/(B_c \tau_c + \gamma P)^2
\]

(33)

In Equation (33), if the following conditions are met, \( S_1'(P) > 0 \):

\[
S - \beta + (\theta \ln \gamma - 1) (1 - \tau + \tau_m) < 0
\]

(34)

\[
S - 1/\theta + (\theta \ln \gamma - 1) (1 - \tau + \tau_c) < 0
\]

(35)

In accordance with the income matrix, we extend Formulas (34) and (35) as follows:

\[
(B_m + I_m \theta \ln \gamma - I_m) (1 - \tau + \tau_m)
+ S I_m - B_m (1 - \tau + \tau_m) < \beta I_m
\]

(36)

\[
(B_c + I_c \theta \ln \gamma - I_c) (1 - \tau + \tau_c)
+ S I_c - B_c (1 - \tau + \tau_c) < I_c/\theta
\]

(37)

In Equations (36) and (37), when the government provides a composite subsidy, the after-tax income of each enterprise’s R&D investment is still lower than the risk caused by technology spillover or R&D cost. Under these conditions, increasing the industrialization scale subsidy rate \( P \) will increase the area \( S_1 \) and reduce the probability of Positive Cooperation between the military and civilian enterprises. However, in contrast to the single subsidy, in the composite subsidy policy, we observe that an increase in the input-output rate of R&D and in the tax subsidies will increase the income of the military and civilian enterprises. Improvement of the input-output rate of R&D is an essential factor in promoting cooperation in innovation. Once industrialization (i.e., production) begins, the subsidy policy given by the government should focus on tax subsidies. The scale subsidy can also play a positive role when the basic income has grown to the point of covering the risk costs of R&D investment.

In Equation (33), if the following conditions are met, \( S_1' > 0 \):

\[
S - \beta + (\theta \ln \gamma - 1) (1 - \tau + \tau_m) > 0
\]

(38)

\[
S - 1/\theta + (\theta \ln \gamma - 1) (1 - \tau + \tau_c) > 0
\]

(39)

In accordance with the income matrix, we extend Equations (38) and (39) as follows:

\[
(B_m + I_m \theta \ln \gamma - I_m) (1 - \tau + \tau_m)
+ S I_m - B_m (1 - \tau + \tau_m) > 0
\]

(40)

\[
(B_c + I_c \theta \ln \gamma - I_c) (1 - \tau + \tau_c)
+ S I_c - B_c (1 - \tau + \tau_c) > 0
\]

(41)
In Equations (41) and (42), the after-tax income of each enterprise’s R&D investment is higher than the risk cost caused by technology spillover or R&D cost. Under these conditions, increasing the industrialization scale subsidy rate \( P \) will reduce the area \( S_1 \) and increase the probability of Positive Cooperation between the military and civilian enterprises. Meanwhile, Equation (33) shows that, under the composite subsidy policy, increases in the industrialization scale subsidy, the tax subsidy, and the R&D subsidy will accelerate the rate at which the probability of a Positive Cooperation strategy on the part of each enterprise increases. Therefore, when the military and civilian incomes each achieve a certain level, policies on taxation and industrialization relevant to that income level should be introduced promptly, the better to improve the stability of the innovation system.

3) THE TAX SUBSIDY RATE
The impact of the tax subsidy rate on military-civilian collaboration in innovation is analyzed here.

For military enterprises, the change of the area \( S_1 \) with \( \tau_m \) can be derived as follows:

\[
S'_1 (\tau_m) = -I_m \{ (\theta \ln \gamma - 1) [(1 - \tau) B_m - \gamma P] + (S - \beta) B_m \} / (2(B_m \tau_m + \gamma P)^2)
\]  

(42)

For civilian enterprises, the change of the area \( S_1 \) with \( \tau_c \) can be derived as follows:

\[
S'_1 (\tau_c) = -I_c \{ (\theta \ln \gamma - 1) [(1 - \tau) B_c - \gamma P] + (S - 1/\theta) B_c \} / (2(B_c \tau_c + \gamma P)^2)
\]  

(43)

According to Equations (42) and (43), if the following conditions are met, \( S'_1 (\tau_m) > 0 \) and \( S'_1 (\tau_c) > 0 \):

\[
(\theta \ln \gamma - 1) [(1 - \tau) B_m - \gamma P] + (S - \beta) B_m < 0
\]  

(44)

\[
(\theta \ln \gamma - 1) [(1 - \tau) B_c - \gamma P] + (S - 1/\theta) B_c < 0
\]  

(45)

According to the income matrix, we extend Equations (39) and (40) as follows:

\[
(1 - \tau) B_m + (1 - \tau) (\theta \ln \gamma - 1) I_m + \gamma P - \beta I_m + S I_m - [(1 - \tau) B_m + \gamma P] < \gamma P (\theta \ln \gamma - 1) I_m / B_m
\]  

(46)

\[
(1 - \tau) (\theta \ln \gamma - 1) I_c + (1 - \tau) B_c + \gamma P - I_c / \theta + S I_c - [(1 - \tau) B_c + \gamma P] < \gamma P (\theta \ln \gamma - 1) I_c / B_c
\]  

(47)

As with the case of the single subsidy, in Equations (48) and (49), if the after-tax income from R&D investment carried out by the military and civilian enterprises is low, the probability of stable convergence on a Positive Cooperation equilibrium will decrease as the tax subsidy rates \( \tau_m \) and \( \tau_c \) increase.

However, further analysis shows that other subsidies in the composite subsidy regime can alter the situation that has just been described. Under the conditions of Equations (48) and (49), R&D investment income will be low and may even produce a loss when the input-output rate of R&D is low. In that case, increasing R&D investment subsidies can make up for the loss of income, and promote continued investment in R&D by the military and civilian enterprises. Therefore, when the military-civilian collaborative innovation organization has not yet been formed, or when the project is a challenging one to tackle by virtue of a low R&D input-output rate, the government should provide the military and civilian enterprises with R&D investment subsidies. This will assist in forming the innovation organization and smooth the start of the science and technology research projects. Should the input-output efficiency improve, a preferential tax policy will become effective in promoting cooperative innovation.

According to Equation (37), if the following conditions are met, \( S'_1 (\tau_m) < 0 \) and \( S'_1 (\tau_c) < 0 \):

\[
(\theta \ln \gamma - 1) [(1 - \tau) B_m - \gamma P] + (S - \beta) B_m > 0
\]  

(48)

\[
(\theta \ln \gamma - 1) [(1 - \tau) B_c - \gamma P] + (S - 1/\theta) B_c > 0
\]  

(49)

In accordance with the income matrix, we extend Equations (43) and (44) as follows:

\[
(1 - \tau) (\theta \ln \gamma - 1) I_m + (1 - \tau) B_m + \gamma P - \beta I_m + S I_m - [(1 - \tau) B_m + \gamma P] > \gamma P (\theta \ln \gamma - 1) I_m / B_m
\]  

(50)

\[
(1 - \tau) (\theta \ln \gamma - 1) I_c + (1 - \tau) B_c + \gamma P - I_c / \theta + S I_c - [(1 - \tau) B_c + \gamma P] > \gamma P (\theta \ln \gamma - 1) I_c / B_c
\]  

(51)

According to Equations (50) and (51), when the military and civilian enterprises have high returns after investing in R&D costs, the probability of Positive Cooperation between the military and civilian enterprises will grow with the increase of the tax subsidy rate. Additionally, in a composite subsidy regime, when the scale subsidy rate \( P \) increases, the probability of Positive Cooperation in the military-civilian innovation will be enhanced.

VI. MATLAB NUMERICAL SIMULATION ANALYSIS
A. EXPERIMENTAL PARAMETER DESIGN
Based on the above analysis of the evolutionary model of military-civilian collaborative technological innovation, we assigned parameters and performed numerics simulations of the evolutionary process under different conditions. We used Matlab software to simulate the dynamic evolution of the strategies selection of both the military and civilian enterprises, and the influence of each parameter on evolutionary stability was analyzed further.

We assumed that the probability of the military enterprise adopting the Positive Cooperation strategy was \( x \) and that of the civilian enterprise was \( y \). The initial values \( (x, y) \) of the simulation experiment were \((0.5, 0.5), (0.3, 0.6), (0.6, 0.3), (0.8, 0.4) \) and \((0.4, 0.8) \) respectively, and the simulation range of the time variable was in the range of \([0, 10]\). The horizontal and vertical axes in Figs. 2-4 represent the local values of \( x \) and \( y \), respectively. The dynamic processes whereby these
four initial points evolve toward equilibrium are simulated in \([0,1] \times [0,1]\) coordinate space. Since \((0,0)\) and \((1,1)\) are two asymptotic stability points of the system, we design two groups of experimental data to investigate the evolution of the system toward those two asymptotes.

Design of the first set of parameters: For the process of evolution to the equilibrium point \((0,0)\), we set the parameter values as follows: \(\tau = 0.13, \tau_m = \tau_c = 0.05, B_m = B_c = 40, l_m = l_c = 5, S = 0.2, \beta = 0.5, \theta = 0.8, P = 0.1, \gamma = 2\). We designed this set of parameter settings under the constraints of Equations (38) and (39).

Design of the second set of parameters: For the process of evolution to the equilibrium point \((1,1)\), we set the parameter values as follows: \(\tau = 0.13, \tau_m = \tau_c = 0.05, B_m = B_c = 40, l_m = l_c = 5, S = 0.2, \beta = 0.5, \theta = 0.8, P = 0.1, \gamma = 20\). We designed this set of parameter settings under the constraints of Equations (38) and (39).

B. SIMULATION EXPERIMENT ANALYSIS

1) EVOLUTIONARY PATH ANALYSIS

We simulated the evolutionary path of military and civil enterprise decision-making under the first set of parameters. Fig. 2 shows the evolutionary path of the military and civilian enterprises from different experimental starting points to the equilibrium point \((0, 0)\).

![FIGURE 2. The evolutionary path of Passive Cooperation between the military and civilian enterprises.](image)

We observe that when the initial value of \(x\) is high, and the initial value of \(y\) is low, the value of \(y\) decreases rapidly on the evolutionary pathway, while the value of \(x\) only decreases slowly by comparison. That is, the trend by which the civilian enterprise chooses Passive Cooperation increases rapidly, and the trend by which the military enterprise chooses Passive Cooperation increases slowly. Finally, both parties tend to \((0,0)\). However, when the initial value of \(x\) is low, and \(y\) is high, this does not lead to a symmetrically similar evolutionary path, even from a symmetrically opposite experimental starting point. In this case, the trend by which the military enterprise evolves to Passive Cooperation is only a little more rapid than that of the civilian enterprise. When \((x, y)\) is close to the point equilibrium \((0,0)\), the decline rate of the civilian enterprise is still higher than that of the military.

It follows that civilian enterprises show greater investment risk aversion. When income is low, the military enterprise tends to adopt Passive Cooperation because of the Passive Cooperation of the civilian enterprise, which reduces technology spillover income. However, the military enterprise shows low sensitivity to investment risk by comparison, leading to a response which is relatively gentle compared to the civilian enterprise.

Fig. 3 shows the evolutionary paths of the military and civilian enterprises from different initial experimental points to the equilibrium point \((1, 1)\) under the second set of parameters. We observe that the value \(x\) increases rapidly while the value \(y\) increases slowly during the evolution of all experimental points to the stable point. In other words, the trend of the military enterprise choosing Positive Cooperation increases significantly. In contrast, the evolutionary trend of the civilian enterprise choosing Positive Cooperation is relatively gentle. Finally, both sides tend to the equilibrium point \((1, 1)\).

Fig. 3 shows that even if the expected return exceeds the primary return and the risk cost of R&D investment, the civilian enterprise is still highly sensitive to investment risk and will maintain a cautious attitude toward R&D investment. The military enterprise shows low sensitivity to the risk of R&D investment. When the income of the military enterprise is sufficient to cover the risk of technology spillover, it will actively invest in R&D. This characteristic of the military enterprise will drive the civilian enterprise to cooperate with the military to carry out scientific and technological innovation activities.

2) THE EFFECT OF R&D SUBSIDY RATE ON THE EVOLUTIONARY PROCESS

Figs. 4 (a), (c) and (e) respectively show the influence of the R&D subsidy rate on the military-civilian evolutionary
We observe that when the industrialization scale $\gamma$ is large, the convergence rate of the evolutionary path of the civilian enterprise increases to some extent with an increase in $S$. The
R&D subsidy rate will encourage the civilian enterprise to invest in R&D. In contrast, the increase of the R&D subsidy rate will harm the military enterprise. The overall rate at which the military and civilian enterprises tend to a stable Positive Cooperation equilibrium slows down.

Figs. 4 (b), (d), and (f) shows the influence of the R&D investment subsidy rate on the evolutionary process under the first set of parameters by modeling changes in $S$. As can be seen from Figs. 4 (b), (d), and (f), when the scale of production is small, the speed with which the civilian enterprise tends to Passive Cooperation is significantly accelerated with the increases in $S$. The reason for this is that when the industrial scale is small, the benefits obtained by both enterprises are low, and the increase of R&D subsidies given by the government will lead to higher benefits even if the investment is slight. However, increasing R&D investment will significantly increase the R&D risks of civilian enterprises while reducing their R&D investment and enjoying the technology spillover brought by the other party’s R&D investment become the best choice for civilian enterprises. Therefore, such a condition will reduce the enthusiasm of the civilian enterprise for R&D investment and eventually tend to Passive Cooperation on the part of the civilian enterprise.

It can be seen from the experiments under both sets of parameters in Fig. 4 that the response of the civilian enterprise to R&D subsidies is relatively sensitive, while that of the military enterprise is relatively insensitive. R&D subsidies thus have a somewhat negative effect on the evolutionary process, by which is meant that they tend to favor convergence on Passive Cooperation and retard convergence on Positive Cooperation, through promotion of free-riding on the part of the civilian enterprise.

3) THE IMPACT OF SCALE SUBSIDIES ON EVOLUTIONARY PROCESSES

Fig. 5 shows the influence of the scale subsidy rate on the evolutionary process, under the second set of parameters, by modeling changes in $P$. Overall, in a manner consistent with the results in Fig. 3, the evolution of the military enterprises converges more rapidly upon the final equilibrium. The convergence rate of both enterprises increases monotonically with increase in $P$, and the acceleration of the civilian enterprise’s convergence is more evident than that of the military enterprise. Increasing the scale subsidy rate will increase the income of both enterprises. However, the acceleration of the
convergence rate of the civilian enterprise is higher than that of the military enterprise, although the convergence rate of the civilian enterprise is still lower than that of the military enterprise. This phenomenon indicates that the civilian enterprise is more sensitive to income. Therefore, the increase in scale subsidies can promote Positive Cooperation between the military and civilian enterprises. Additionally, we observe that the incentive effect of the scale subsidy upon the civilian enterprise is more significant than that upon the military enterprise.

4) THE EFFECT OF THE TAX SUBSIDY RATE ON EVOLUTIONARY PROCESS

(1) The effect of the tax subsidy rate upon military enterprises. Fig. 6 shows the evolutionary effect of the tax rate subsidy rate, under the second set of parameters, upon the evolutionary process of the military enterprise. As shown in Fig. 6, the convergence rate of the military enterprise increases with increase in $\tau_m$, but the degree of acceleration shown is only slight. The military enterprise will obtain higher returns, as compared to its original returns, with increasing tax subsidies given by governments. Thus, the tax subsidy will promote the R&D investment of military enterprises. However, due to a low sensitivity to income, the impact of the tax subsidy rate on the decision of military enterprises is not pronounced.

(2) The effect of the tax subsidy rate upon civilian enterprises. Fig. 7 shows the influence of the tax rate subsidy rate, under the second set of parameters, upon the evolutionary process of the civilian enterprise. We observe from Fig. 7 that the convergence rate of the civilian enterprises accelerates both markedly and monotonically with increase in $\tau_c$. The response of the civilian enterprise to the tax subsidy rate is more sensitive than that of the military enterprise.

5) THE EFFECT OF THE TECHNOLOGY SPILLOVER RATE ON EVOLUTIONARY PROCESS

Fig. 8 shows the influence of the technology spillover rate on the evolutionary process, under the second set of parameters. Fig. 8 (b) shows that the convergence rate of the evolutionary process increases significantly for the civilian enterprise with increase in $\beta$, while that of the military enterprise decreases.
to a certain extent as shown in (a). It is part of our model that the military enterprise is more cautious about technology spillovers than the civilian enterprise. In the evolutionary process, the risk of technology spillover will dampen the willingness of the military enterprise to invest in R&D. However, technology spillover means an increase in revenue for the civilian enterprise. Hence, the technology spillover rate plays a positive role in the R&D investment of the civilian enterprise.

6) THE IMPACT OF THE R&D INPUT-OUTPUT RATE ON THE EVOLUTIONARY PROCESS

Fig. 9 shows the influence of the R&D input-output rate on the evolutionary process under the second set of parameters. Fig. 9 shows that the convergence properties of the military (a) and civilian (b) enterprises differ markedly with increasing $\theta$. After a rapid initial jump, the convergence of the military enterprise thereafer accelerates only slightly. For its part, the civilian enterprise displays two equilibrium end-states, an outcome which can be explained as follows. The cost risk of R&D investment, to which the civilian enterprise is sensitive, will drop significantly as the input-output rate of R&D investment increases. Therefore, the R&D income of the civilian enterprise will increase, and this will enhance the willingness of the civilian enterprise to cooperate positively. In more detail, Fig. 9 (b) shows that when $\theta$ drops below a certain threshold, which lies between 0.7 and 0.75 in this simulation, the civilian enterprise will converge upon Passive Cooperation, and that with further decline in $\theta$, the convergence upon Passive Cooperation will accelerate.

VII. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

This paper establishes an evolutionary game model of military-civilian integration: that is to say, of collaborative technological innovation involving a representative military enterprise and a civilian enterprise. On the basis of this model, we analyze the impact of various subsidy policies on the cooperative behavior of the military and civilian enterprises.

(1) This paper describes our evolutionary game model of military-civilian integration, and then proceeds to analyze the stability of the evolutionary process of military-civilian cooperation. The results show that Passive Cooperation by both enterprises (i.e., mutual free-riding), and Positive Cooperation by both enterprises (a more actively cooperative outcome), are the two asymptotic stability points or equilibria of the system. Policy factors such as the R&D investment subsidy rate, the scale subsidy rate, and the tax subsidy rate are seen to impact the system’s evolution toward one or other of the two equilibria.

(2) On the basis of the evolutionary game model, the impact of various subsidy policies was analyzed. Firstly, the results show that R&D subsidy can stimulate enterprises to invest in technological innovation from a static perspective. However, from the perspective of evolution, excessive or overly prolonged R&D subsidy harms both military and civilian cooperation in pursuit of innovation by generating free-rider effects. This form of harm can be reduced by a transition to tax subsidies and scale subsidies as the system moves toward industrial implementation. Secondly, tax subsidies will play a positive role after the input-output rate of R&D of innovation cooperation has been improved and substantial economic revenues have been generated. Tax subsidies can also cushion the fade out of R&D subsidies as these are withdrawn. Thirdly, the scale subsidy, which rewards the upscaling of production, can significantly improve the income level of military and civilian enterprises in the industrialization (production) stage of the new technology’s introduction, thus also accelerating and locking in a regime of Positive Cooperation between the military and enterprises.

(3) The influence of the above subsidy policy changes on military-civilian integration was analyzed through MATLAB simulation experiments. Firstly, our simulation results showed that civilian enterprises display high sensitivity to the three kinds of subsidies, while military enterprises have no significant response. When the military-civilian enterprise pair evolves toward a Positive Cooperation equilibrium, the convergence rate of the military enterprise is significantly higher than that of the civilian enterprise.

However, when the military-civilian enterprise pair evolves toward the Passive Cooperation equilibrium, the convergence rate of the civilian enterprise is markedly higher than that of military enterprises. This finding indicates that the military enterprise is dominant in the establishment of the Positive Cooperation strategy. In contrast, the civilian enterprise is susceptible to cost risks and has an evidently cautious, wait-and-see attitude toward Positive Cooperation.

Secondly, through further analysis of simulated parameters, it became clear that improving the input-output rate of R&D, that is to say its actual industrial payoff, can reduce the risk cost of the civilian enterprise and stimulate the civilian enterprise’s enthusiasm for R&D investment. An increase in the technology spillover rate can also observably stimulate the R&D investment intention of civilian enterprises. On the other hand, the military enterprise shows a high negative sensitivity to the technology spillover rate, and this acts as a countervailing factor.

B. THEORY AND PRACTICAL CONTRIBUTIONS

(1) We have constructed a subsidy model for military-civilian integration, based on a detailed investigation and summary of China’s current subsidy policies.Unlike most existing studies that only consider a single subsidy [25], we have constructed a complex government subsidy mechanism which follows the development process from early R&D inception through to industrial implementation. Our study of the subsidy mechanism establishes a theoretical basis for analysis of such a complex subsidy mechanism. Our study of subsidy mechanism can facilitate a more scientific observation of the impact of different types of subsidies on cooperative innovation, and
provide a decision-making basis by which the government may establish a more evidence-based subsidy mechanism.

(2) We built an evolutionary game model and conducted evolutionary analysis based on the different characteristics of military and civilian actors. In contrast to the symmetric game model in the existing research [22], we have described the different attitudes of military and civilian actors toward technology spillovers and R&D investment in our model, and thus built an asymmetric evolutionary game model. Therefore, in our simulation analysis, there are significant differences in the sensitivity of the two representative enterprises in terms of convergence speed, subsidies, technology spillover level, and R&D efficiency. Our study reveals the complexity of technical cooperation between heterogeneous partners and provides a decision-making basis for the government to adopt different incentive methods and supporting measures for different groups.

C. RECOMMENDATIONS

On the basis of our evolutionary game model, we offer the following recommendations for the civilian and military sectors.

(1) For the civilian sector, governments should scientifically plan a diversity of special funds and subsidies and make plans that allow for the timing of these forms of assistance with reference to the stages of the innovation process.

Firstly, in the early stage of scientific and technological innovation, R&D-related subsidy policies, such as pre-research funds and pre-research project subsidies, should be issued in stages and fields to encourage civilian enterprises to carry out scientific and technological innovation. After forming an organization to manage the innovation system, it is also necessary to strengthen the regulation of subsidized funds for pre-research projects and to ensure the guidance of subsidy funds for enterprise R&D investment. The government should also arrange to fade out R&D subsidies in a timely manner and mobilize autonomous (endogenous) enterprise R&D investment through financing, credit, and other financial policies.

Secondly, civilian enterprises show high sensitivity to R&D risk, even though they also profit from the benefits. Therefore, governments should pay more attention to constructing military and civilian integration platforms that share resources such as laboratories and large equipment, and to promoting military-civilian alignment. Such measures will promote the formation and stable development of the military-civilian innovation system, enhance the level of technology spillover between military and civilian enterprises, and reduce production and R&D costs.

Thirdly, in the initial stage of industrialization (production), when the scale of production is small, and the income level is low, the government should focus on tax policies to promote innovation, such as VAT (sales tax) reduction, tax exemptions, and additional deductions. These policies can improve the enthusiasm for autonomous R&D investment to a certain extent. Furthermore, the government should consider the comprehensive application of tax subsidies, R&D subsidies, and other policies to help enterprises get through this difficult stage when investment is large and returns are low.

Fourthly, when industrialization has increased in scale, and when the income of the enterprise has increased accordingly, the role of a scale subsidy, to support further scale-up, will become significant. At the same time, the comprehensive application of tax subsidies, R&D subsidies, and other policies may still be required. A sensitive mixture of a range of incentives, tailored to the stages of innovation, can thus improve the effectiveness of innovation policies.

(2) The military sector shows relatively low sensitivity to the various subsidy policies we have canvassed, but a high sensitivity to technology spillover, which it perceives negatively. Therefore, while “removing barriers, breaking the ice, and removing thresholds,” the government should strengthen the confidentiality governance of military-civilian integration projects to ensure the safe implementation of military-civilian collaboration, from the military’s point of view.

Firstly, in the early stage of forming the collaborative technology innovation organization, most civilian enterprises merely provide R&D and production support of non-core components for the military enterprises. Therefore, in addition to strengthening R&D subsidies for civilian enterprises, the government should construct military-civilian integration service platforms for confidentiality training and other specialized work to establish a foundation for in-depth technical cooperation.

Secondly, in the development stage of joint innovation system, the government should improve the construction of military-civilian integration service platforms to strengthen precise docking and to help share technical resources. To strengthen the function of third-party risk assessment of service platforms, governments should regularly conduct risk assessment on all aspects of military-civilian collaboration and put forward prevention and control measures to reduce enterprises’ technology spillover risk.

Thirdly, in the industrialization (production) stage of military-civilian integration technological innovation, it is necessary to strengthen the supply of useful policies to scale-up industrial production. Governments should establish industrial alliances, perfect supporting systems, and reduce the costs faced by enterprises of the kind that act as barriers to the upscaling of industrial production.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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