Discussion of the Cross-Domain F5 Kill Chain Problem for Time-Sensitive Targets

Cheng Zhenyu[1,*], Ji Ming[2], Xu Junyi[2]

[1]Chinese Academy of Military Science, Troop NO.91286, Beijing, China

[2]Chinese Academy of Military Science, Beijing, China

*chengzhenyucs@163.com

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Abstract: In response to the challenge of constructing a kill chain in scenarios involving multiple batches of time-sensitive targets, we have analyzed the limitations of the traditional F2T2EA kill chain model in the context of future combat scenarios. Subsequently, we propose a theoretical model for a cross-domain F5 kill chain specifically tailored to address time-sensitive targets. In the technical realm, we have developed a mathematical model that takes into account the threat level posed by incoming targets. This model can rapidly generate the required kill chain to meet the demands of modern operations, utilizing the Monte Carlo search algorithm. Furthermore, we have applied concepts from complex network modeling and group replacement theory and implemented a sliding window mechanism to construct a mathematical model capable of quickly generating the necessary kill chain to address the operational needs of this new era.

1. Introduction

Since the Gulf War, targeting time-sensitive objectives has become a pivotal aspect of modern warfare, with time-sensitive targets accounting for over 60% of engagements in the Iraq War and up to 90% in the Syrian War. When faced with multiple waves of time-sensitive targets, joint combat forces are often left with only a narrow time window for response. The U.S. Army Joint Publication JP3-60, titled “Joint Targeting Orders”, emphasizes that the most salient characteristic of time-sensitive targets (TST or TCT) is their susceptibility to time-based vulnerabilities. Moreover, the dynamic nature of today’s operational environments has intensified the challenges associated with meeting time constraints for engaging potential or designated targets.

This paper centers on the fundamental time-related characteristics of time-sensitive targets. It conducts a theoretical analysis of the limitations of the traditional F2T2EA kill chain model and proposes a cross-domain F5 kill chain theoretical model tailored for time-sensitive targets. On the technical front, we employ complex network modeling techniques, group replacement theory, and the sliding window mechanism. Leveraging the Monte Carlo search algorithm, we factor in threat levels to delineate potential threats and accordingly construct a relevant mathematical model. This enables the rapid generation of the required kill chain.

2. Problem Statement

Modern warfare scenarios are increasingly characterized by cross-domain operations, and the temporal nature of time-sensitive targets makes the dynamic generation of cross-domain kill chains a critical concern for military forces worldwide.

In contrast to traditional linear kill chains, which are typically pre-constructed based on plans during combat preparation, cross-domain kill chains are more likely to be dynamically generated. The predictability of static linear links and their vulnerability to disruption under intense combat conditions make them less suitable for modern warfare. Cross-domain kill chains offer several advantages, including network cross-domain empowerment, diversified means selection, and

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enhanced functional efficiency. They enable the rapid and rational allocation of combat resources within the constraints of limited battlefield resources. They also facilitate the transformation of traditional linear kill chains into dynamic kill chains or even kill networks, allowing for swift and high-quality closure of the kill chain. This approach empowers cross-domain combat capabilities and maximizes system effectiveness. Therefore, effective utilization of battlefield resources, dynamic construction of cross-domain kill chains, and continuous improvement of kill chain closure capabilities are pivotal in securing victory in future wars.

In this research, we concentrate on addressing the challenges of achieving effective cooperation among combat units, optimizing the allocation of battlefield resources, and swiftly closing the kill chain in scenarios involving multiple waves of time-sensitive targets. We acknowledge that each component within the kill chain possesses its unique attributes and capabilities. Hence, our focus is on the real-time and dynamic generation of cross-domain kill chains involving these combat units.

3. Theoretical modeling of cross-domain f5 kill chain for time-sensitive targets

The U.S. military has proposed the F2T2EA kill chain model, which is relatively mature for addressing strike requirements in scenarios involving incoming time-sensitive targets. However, this model still suffers from certain shortcomings, including complex internal logic within its links and functional overlap among some of these links. Moreover, the model struggles to effectively and simultaneously engage various intelligent equipment when dealing with multiple waves of incoming time-sensitive targets. To address these limitations, this section introduces a theoretical model for a cross-domain F5 kill chain tailored to the needs of time-sensitive targets. This model aims to rectify the deficiencies of the traditional F2T2EA kill chain model in response to specific scenario requirements.

3.1 The F2T2EA Kill Chain Model

The increasing presence of time-sensitive targets, such as over-the-horizon long-range high-mobility fire strike platforms, on the battlefield underscores the growing importance of swift and agile kill chain closure. Field data from the U.S. Army during the Syrian war revealed that time-sensitive targets constituted 90% of the total target ratio. The substantial number of dynamic time-sensitive targets made it evident to the U.S. Army that successfully striking such targets required a well-organized, well-rehearsed, and mature set of procedures.

In response to the need for effectively striking time-sensitive targets, the U.S. Air Force introduced the F2T2EA kill chain model in 1990. This model was designed based on the concept of the joint target work cycle. It notably addressed the challenge of extended response times, from target detection to the initiation of strike actions, when dealing with time-sensitive targets.

The F2T2EA model operates in six steps, namely Find, Fix, Track, Target, Engage, and Assess (See Figure 1):

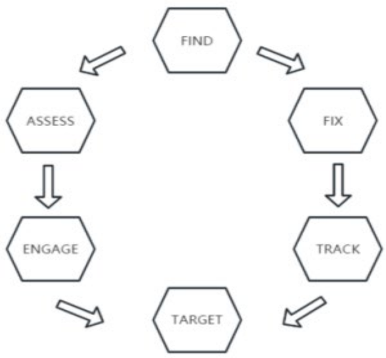

Fig. 1 The model of F2T2EA kill chain

Find: This step involves detecting and identifying a potential target on the battlefield. Further intelligence collection and analysis are conducted to determine if the target meets the criteria for dynamic targeting.

Fix: In this step, the location of the potential target is determined, taking into account its temporal characteristics and threat level. Priority is given to processing time-sensitive targets.

Track: Continuous tracking of the target's location and trajectory is carried out in this step.

Target: Here, decisions are made on how to strike the target to achieve the desired effect. The commander selects the optimal striking approach based on battlefield conditions and other relevant decision-making information.

Engage: This step involves taking military action against the target to ensure that the corresponding forces are informed and fully prepared for the combat task.

Assess: In the final step, a preliminary assessment of the action taken against the target is conducted.

3.2 Cross-Domain F5 Kill Chain Model in the Context of Intelligent Warfare

The result is the Cross-Domain F5 Kill Chain Model (Find, Fix, Fire, Finish, Feedback) [1], tailored to meet the operational requirements of countering incoming time-sensitive targets in the context of intelligent warfare (See Figure 2).

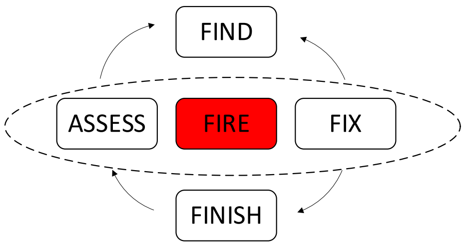

Fig. 2 The model of F5 kill chain

Firstly, the F5 kill chain model simplifies the Track link within the traditional F2T2EA kill chain model. With the rapid advancement of information technology, battlefield sensors are no longer scarce resources. When a target is locked (Fix) by a sensor, it can be continuously tracked without the need for coordinating sensor usage through a separate tracking link. Consequently, in the F5 kill chain model, the Track link becomes an implicit sub-function of the Fix link, simplifying the process and expediting kill chain closure.

Secondly, the F5 kill chain model breaks down and consolidates the functions of the targeting link present in the traditional F2T2EA kill chain model. At the tactical level, the targeting link's function involves assigning the target to a chosen target-striking link and transmitting the targeting information obtained by the sensor to the shooter. From this perspective, this function can be disassembled and integrated into implicit subsets of both the Fire and Fix links.

Thirdly, the F5 kill chain model eliminates the human element from the targeting aspect of the traditional F2T2EA kill chain model. In combat operations, the targeting link involves tasks such as selecting identified, classified, located, and prioritized targets, determining strike effects, creating a strike plan, and obtaining required approvals before engaging in operations. These tasks often incorporate rules of engagement approved in advance, which are not inherent to the kill chain itself but are external variables. The F5 kill chain model explicitly recognizes authorization operations (Approval) as external variables that can be inserted between chain links as needed. It is essential to emphasize that abstracting the human factor into Approval does not diminish its importance but rather incorporates human involvement in the kill chain as an external variable. This approach allows algorithms to be designed for rapid optimization while preserving the commander's critical role in combat actions. The concept of "human in the loop" is integral to the F5 kill chain model, ensuring that human decision-making remains a central element.

3.3 Description of Scenarios for the Utilization of Different Types of Equipment under the F5 Kill Chain Model

As depicted in Figure 3, for conventional weapons like land helicopters engaging land maneuvering targets, both the launch and strike occur simultaneously. In this scenario, the model transforms into “discovery, locking, (authorization), launching, completion, and feedback”.

For semi-autonomous weapons, such as those launched after target discovery with intelligence support from ISR and striking autonomously after locking onto the target, the model becomes “discovery, launching, locking, (authorization), completion, and feedback”.

In the case of highly intelligent and fully autonomous weapons like intelligent patrol bombs equipped with autonomous identification, detection, localization, and strike capabilities, the model changes to “launch, discovery, locking, (authorization), completion, and feedback”.

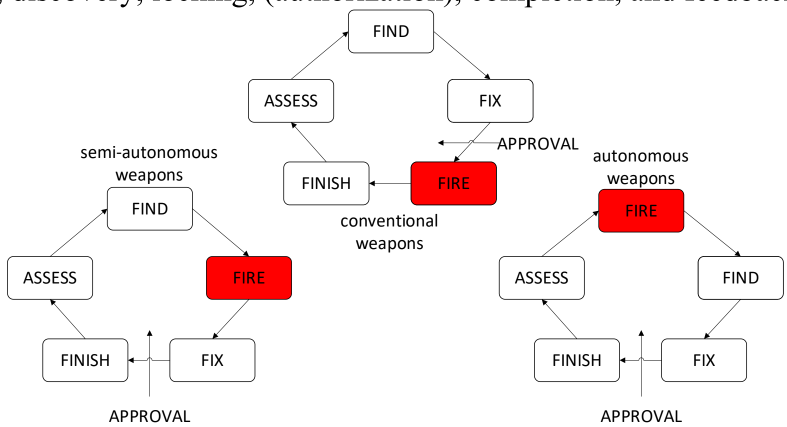

Fig. 3 Three variants of the F5 kill chain model

As intelligent and unmanned equipment continues to proliferate on the battlefield, the challenge of orchestrating the kill chain closure across a vast equipment network grows. This poses significant challenges to human cognition and decision-making. Moreover, for time-sensitive targets with extremely tight deadlines, achieving rapid kill chain closure may surpass the limits of human cognition and decision-making. To address this, corresponding algorithms must be designed based on the theoretical model. These algorithms, combined with the computational power of computers, can rapidly facilitate kill chain closure, aiding commanders in identifying optimal strike programs.

4. Mathematical modeling of cross-domain F5 kill chain against multiple batches of time-sensitive targets

This section proposes a dynamic generation algorithm for cross-domain F5 kill chain of time-sensitive targets based on group permutation theory. Firstly, the requirements of cross-domain kill chain are analyzed. Then, based on the F5 kill chain model, the cross-domain collaborative process is transformed into a sequential decision problem. Following the sequential decision process of the F5 kill chain, the kill chain of time-sensitive targets under multiple batches of attacks is modeled by combining the group permutation theory and complex modeling methods.

4.1 Cross-Domain Kill Chain Modeling for Multiple Batches of Time-Sensitive Targets Based on Group Replacement Theory

In this approach, combat units within each physical domain are depicted as nodes in the network, while the information interaction links in the information domain are represented as edges.

The time-sensitive nature of the targets requires a high level of closure in the kill chain within a specified time limit, which can be defined by integrating a threat utility function. Assuming that each time-sensitive target has m threat attributes such as speed, distance, quantity, batch, and killing capability, considering that the threat level of incoming time-sensitive targets is not constant and varies over time. Different weights are assigned to the threat attribute indicators based on their importance, with the weight values being constants. The comprehensive threat level of a specific time-sensitive target at time t is obtained by summing the weighted values of its various threat attributes.

Assuming that each time-sensitive target has m classes of threat attributes, and letting them be , are the weights of the ith threat attribute, respectively, then the combined threat utility function is

$$\omega(t) = \sum_{i=1}^{m} \alpha_i \omega_i(t) \quad (1)$$

Using the comprehensive threat degree function for time-sensitive targets, the Service can calculate the comprehensive threat degree for each time-sensitive target and then compare these targets to identify those with the highest threat degree. At the initial moment t_1, it is observed that there are n_1 time-sensitive targets with threats, sorted by their threat degrees at the current moment, and denoted as $A_{11} \geq A_{12} \geq \ldots \geq A_{1n_1}$. In this scenario, we can adopt an action plan that prioritizes striking high-threat targets. This means that the first wave of strikes will prioritize A_{11}, and the time allocated for these strikes forms the initial strike window. Subsequent strikes will be carried out sequentially based on the threat degree ordering within the time limit. If it is not possible to complete all strikes within the current time window due to limited combat resources, those remaining will be deferred to the next wave of strikes.

Within the constraints of limited battlefield resources, an improved algorithm is proposed based on group replacement theory. This algorithm dynamically selects the optimal group of combat units capable of intercepting multiple batches of incoming time-sensitive targets with the assistance of machine arithmetic. Simultaneously, it enhances the robustness of striking effectiveness.

Utilizing the concept of maximum threat degree and employing the assistance of group replacement theory, the proposed improved algorithm is as follows:

We make our combat system network as $G(V, E(V))$, and the substitution $\sigma(\cdot)$ as an element of the k order substitution group $S(1,2,\ldots,k)$. We assume the binary mapping $T_{1i}\left(G(V, E(V)), (\sigma(1), \sigma(2), \ldots, \sigma(k))\right)$ as the time taken by our combat system network to process the $\sigma(i)$ target goal at $A_{1,\sigma(1),}A_{1,\sigma(2)}, \ldots, A_{1,\sigma(k)}$ according to the Monte Carlo tree algorithm, then let:

$$\Delta t_{11} = \min_{\sigma \in S(1,2,\cdots\cdots,k)} \max_{i \in S(1,2,\cdots\cdots,k)} T_{1i}\left(G(V, E(V)), (\sigma(1), \sigma(2), \ldots, \sigma(k))\right) \quad (2)$$

$$\sigma^* = \arg \cdot \min_{\sigma \in S(1,2,\cdots\cdots,k)} \max_{i \in S(1,2,\cdots\cdots,k)} T_{1i}\left(G(V, E(V)), (\sigma(1), \sigma(2), \ldots, \sigma(k))\right) \quad (3)$$

4.2 Sliding Window Feedback Mechanism for Maximizing Threat Degree

In Section 4.1, we introduced the concept of constructing a cross-domain kill chain for time-sensitive targets based on the group replacement theory. This approach proves effective when dealing with time-sensitive targets that exhibit high homogeneity. However, a challenge arises when certain time-sensitive targets approach the maximum threat degree within the observation timeframe. In such cases, these targets may not be struck within the time window of one wave of attacks and must be retained for the next wave. As time progresses, these targets may accumulate threat degrees exceeding those of the previous wave. If this scenario repeats itself, the effectiveness of our strikes diminishes significantly. To address this issue, we propose the introduction of a sliding window feedback mechanism, similar to those used in network communication. This mechanism incorporates an elastic sliding window for the maximum threat level, helping to avoid potentially uncontrollable situations while minimally impacting the algorithm's ability to dynamically generate the cross-domain kill chain.

By introducing a threshold parameter ε for the sliding window feedback mechanism based on the maximum threat level, such that the

$$k = arg \max_{1 \leq k \leq n_1} \{A_{11} - \varepsilon \leq A_{1k}\} (4)$$

In this scenario, within the combat system network defined in Section 4.1 as $G(V, E(V))$, we raise the qualification threshold parameter ε, expanding the original maximum threat level target into multiple sets of maximum threat level targets. This expansion aims to optimize the algorithm presented in Section 4.1.

4.3 Cross-Domain F5 Kill Chain Link Generation based on Monte Carlo Search Algorithm

Cross-domain F5 kill chain link generation based on the Monte Carlo search algorithm involves the utilization of the[2] domain-wide command and control coordination algorithm proposed by domestic scholars to generate the optimal group of combat units through the selection of optimal nodes . In this algorithm, the optimal combat unit group is formed by selecting the best collaborative nodes, followed by the calculation of the minimum time cost for processing the specified time-sensitive target.

The core of this algorithm is the Upper Confidence Bound applied to Trees (UCT) algorithm, where $Q(\nu_i)$ represents the total simulated utility of the node, $N(\nu_i)$ and $N(\nu)$ represent the total number of visits to nodes ν_i ,ν respectively, and c is a constant.

$$\mathrm{UCT}(\nu_i,\nu)=\frac{Q(\nu_i)}{N(\nu_i)}+c\sqrt{\frac{\log(N(\nu))}{N(\nu_i)}} \quad (5)$$

When dealing with multiple batches of dynamic time-sensitive targets, the specific approach is as follows: First, we input wide-area low-resolution situational awareness intelligence from the ISR intelligence node into the kill chain discovery link. Next, we rapidly evaluate the threat degree of the incoming time-sensitive targets and select the maximum threat target strike group based on the threat degree utility function. Then, we choose a reconnaissance node to continuously track the time-sensitive targets within the maximum threat target group. Subsequently, we transmit visual information to the fire unit to carry out the strike. Finally, the reconnaissance node provides feedback on the damage inflicted on the time-sensitive targets. If it falls short of the target damage requirements, we move on to the next cycle.

We repeat the process by selecting the reconnaissance node to continuously locate and track the time-sensitive target in the largest threat target group. Once again, we transmit visual information to the fire unit for a strike attempt. The reconnaissance node once more provides feedback on the destruction of the time-sensitive target, and if the target destruction requirement is not met, we proceed to the next cycle. Throughout the process of closing the cross-domain kill chain, we adjust the insertion position of the “launch” link and the “approval” operation within the link based on the varying intelligence of the weapon platform.

Following the optimized and improved algorithm in Section 4.2 to derive the set of strike sequences based on the maximum threat ordering, we rank $A_{1,\sigma^*(1)}, A_{1,\sigma^*(2)}, \ldots, A_{1,\sigma^*(k)}, A_{1,k+1}, \ldots, A_{1,n_1}$ sequentially as $B_{11}, B_{12}, \ldots, B_{1,n_1}$. Let $\triangle t_{1j}$ be the time spent by the graph $G\left(V_j, E(V_j)\right)$ to process the target B_{1j} according to the Monte Carlo search algorithm, where $j=k+1,k+2,\ldots,n_1$,$V(B_{1j})$ represents the set of nodes used by the graph $G\left(V_j, E(V_j)\right)$ to process B_{1j} , considering the consumption of node resources in this step. Then V_j has the following recursive equation

$$V_j = V - \bigcup_{i=1,\triangle t_{1i}\le\triangle t_{11}}^{j-1} V(B_{1i}) \quad (6)$$

When $j=1$, and $V_j=V$, then the set of targets processed within the first strike time window $\triangle t_{11}$ is

$$\left\{\bigcup_{i=1}^{k} B_{1i}, \bigcup_{i=k+1,\triangle t_{1i}\le\triangle t_{11}}^{n_1} B_{1i}\right\} \quad (7)$$

The remaining target set is $\bigcup_{i=k+1,\triangle t_{1i}>\triangle t_{11}}^{n_1} B_{1i}$. This concludes the first wave of strike modeling.

The second wave of strikes is modeled as follows: locating $\triangle t_{11}$ withinn_2^* another threatening target is found, then making the

$$n_2 = n_2^* + \sum_{i=1}^{n_1} \mathrm{sign}(\triangle t_{1i} - \triangle t_{11}),\ t_2 = t_1 + \triangle t_{11} \quad (8)$$

Following this, in the second wave at the moment t_2, n_2 reconnaissance units are deployed to address the threat level of the time-sensitive target. The same operation is repeated. In the subsequent waves, denoted as m, the number of reconnaissance units n_m is determined as $n_m = n_m^* + \sum_{i=1}^{n_{m-1}} sign(\triangle t_{1i} - \triangle t_{11})$. These units engage targets with the threat level at the moment $t_m = t_{m-1} + \triangle t_{1,m-1}$ to carry out strikes, following the previously described sequential decision-making method. In this context, n_m^* represents the number of new reconnaissance units added to address the threat level of targets in the m wave, and $\triangle t_{1,m-1}$ accounts for the time consumed by the combat network from the first wave up to the $m-1$ wave of strikes.

5. Conclusion

This paper presents a theoretical model for the cross-domain F5 kill chain concerning time-sensitive targets, focusing on scenarios involving multiple waves of incoming time-sensitive targets on future battlefields. The objective is to efficiently intercept these incoming targets by rapidly closing the kill chain, all within the constraints of limited battlefield resources. To construct this theoretical model, we employ various technical approaches. We utilize complex network modeling, substitution group theory, and sliding window mechanisms. Additionally, we leverage the Monte-Carlo search algorithm to calculate the threat level of incoming time-sensitive targets. This comprehensive approach allows us to build a mathematical model and generate the kill chain swiftly. It is worth noting that while this algorithm performs well in dealing with homogeneous time-sensitive targets, it may exhibit some instability when handling less homogeneous ones. Our next step will involve further enhancing the algorithm to address such scenarios.

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