Research on Real-Time Fusion Technology of Range Telemetry Data

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***Abstract*—Telemetry data is the important data for the ground station to obtain the working status and environmental parameters of the aircraft system. Its fusion processing is the key technology to select the best selection of multiple channels of data and improve the reliability and accuracy of the entire recording. Due to the large amount of telemetry data, there is a delay error in the transmission process, and the phenomenon of frame loss and code error is accompanied by severe challenges for the alignment and optimization of data fusion. The research starts from the application background of fusion technology, introduces and analyzes the characteristics of telemetry data and the difficulties of fusion technology; outlines the current alignment and optimization related research results and development process, according to engineering requirements and technical points, from real-time and after-event From the perspective, the alignment algorithms and quality evaluation algorithms involved are classified and analyzed in detail; finally, the shortcomings of the existing methods are summarized, and the future development direction is looked forward to provide references for related researchers.**

Keywords-Telemetry Data; Data Fusion; Alignment; Optimization

I. INTRODUCTION

The telemetry system is an important part of modern aircraft and aviation weapon launch tests [1]. Over the years, with the continuous running-in and improvement of test tasks, a set of telemetry data processing procedures based on multi-station measurement and control has been formed [5]. As a key technology in the processing process, data fusion mainly selects the best multi-channel data to improve the reliability and accuracy of the whole process [3, 4].

The traditional method of fusion technology is to manually count the errors of a piece of data after the fact, and select the best for splicing [19]. Based on the development of telemetry/computer systems, in 2009, the automatic processing of fusion technology use the "three judgments and two principles", which is a byte-by-byte comparison algorithm for full-frame data (F-frame). Meanwhile, it also exposed a series of problems such as transmission delay, frame loss, and bit errors in the processing process. Establish a standard and unified data quantification method based on the literature [17]. In 2014, literature [13] used theoretical ballistics to characterize the data transmission delay, and divided the fusion technology into two parts: alignment and optimization. Since then, various algorithms in the field of fusion technology have been proposed one after another [7-17], aiming to overcome the difficulties encountered in practical tasks and to develop in a more versatile, efficient and precise direction.

At present, many results have been achieved in the research of fusion technology, but the research content is relatively scattered and fragmented. Therefore, the research starts from the two parts of alignment and optimization involved in data fusion, summarizes the current research status of real-time and after-the-fact fusion processing methods, and elaborates the key algorithms involved. Strive to provide feasible research ideas for the development of data fusion processing technology.

II. TELEMETRY DATA

Telemetry data is usually measured using the PCM system, and the sampling period is milliseconds. The parameters in the same cycle are collected as a frame of PCM data stream, collected again after a certain time interval, and cyclically form the final PCM telemetry data stream, which is recorded in a binary data stream file, and the amount of data is relatively huge.

The processing flow of telemetry data is shown in Figure 1. The Ground Stations (GS) will send the received ciphertext data (C-data) to the command center in real time. Firstly, Passing the decryption pre-processing equipment (DPE) to complete the data encryption independently in parallel, and output the plaintext data (P-data), Then, through the data fusion processing server (DFPS), the multiple channels of plaintext data are clipped to form an optimal whole data stream (O-data), Finally, The central computer system divides the parameters of the whole measurement data (WM-data) flow, calculates, processes and displays the results data(R-data) .

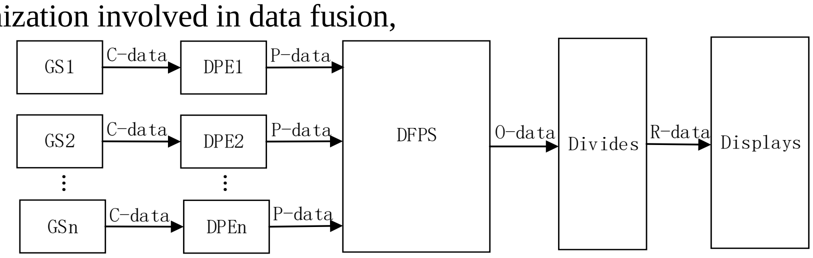

Figure 1. Data processing flowchart

In the data fusion processing, affected by the spatial geographic location of the GS, the data sent by the target at the same time is parsed to the DFPS at a different time, that is the transmission delay. Therefore, the first priority of data fusion is the alignment operation, to match the same-origin frame data sent by different ground stations to receive targets. The main difficulty of alignment lies in the real-time dynamic change of the distance between the target and the GS during the flight, which causes the change of the transmission delay and the possible frame loss and error during data transmission. After alignment, it is necessary to screen the parts with better record quality and complete the whole WM-data splicing, which is called optimization. The key is how to accurately evaluate the quality of the same-origin frames from different GS.

In summary, the data volume of telemetry data is huge, the information processing process is cumbersome, and it is accompanied by frame loss and error and transmission delay. The problems faced by data alignment and optimization processing are complex, and the algorithm is slightly delayed, there will be a cumulative waiting phenomenon, and the fusion time will double, which undoubtedly brings severe challenges to the alignment and optimization of fusion technologies.

III. REAL-TIME ALIGNMENT TECHNOLOGY

Real-time alignment processing must make timely judgments and choices on the currently received limited telemetry data, and the alignment algorithm requires high real-time and reliability. Real-time alignment is often rough, mainly including flag alignment (FA), time code matching alignment (TCMA), and error control alignment (ECA). The following is a key analysis of the real-time alignment algorithm.

A. *Flag alignment (FA)*

The most classic algorithm in FA is the alignment method based on frame count proposed in Literature [21]. Frame counting is a part of telemetry parameters, has continuity and unity at the same time, and its calculation amount is relatively small, the algorithm time complexity is relatively low, and it has become the first choice for real-time alignment technology. But the frame count error is fatal to the algorithm.

Literature [8] optimizes the receiving buffer and the judgment conditions when the frame count is wrong, and reduces the use of computer resources. When the frame count is inconsistent, the smaller frame count is selected as the alignment result data. However, when frame count errors occur continuously in multiple channels of data, this method will cause accumulated frame count errors in the fusion result. As shown in Table I, the frame counts of No. 1 and No. 4 of GS1 have errors, and GS2 Frame count consecutive errors, including data frames No. 2,3, and 4. When frame count alignment is used, the fusion result is 28586, 65467, 65356, 65523 cumulative errors.

TABLE I. ACCUMULATIVE ERROR ALIGNMENT PROCESS

Frame number	GS1	GS2	Fusion result	Correct
1	28586	65530	28586	65530
2	65531	65467	65467	65531
3	65532	65356	65356	65532
4	65523	65533	65523	65533

B. *Time code matching alignment (TCMA)*

The first step of real-time TCMA is performs time code correction, and then, uses the time code matching to align S-frame or F-frame. Reference [21] revises other stations with reference to the time code of the master station frame. This method is easy to implement, but because the time delay of the master station time code in the data transmission process is not considered, the time accuracy of the data alignment result is lost.

C. *Error control alignment (ECA)*

The main idea of real-time ECA is to calculate the time error range in the frame data transmission process, which is called the time delay error range. Based on the frame time code of any station, the corresponding data of the frame time code within the time delay error range is determined as the frame at the same time. As shown in formula:

$$T + \Delta t > T > T - \Delta t \tag{1}$$

T is the reference time, Δt is the time delay error range.

Literature [14] uses theoretical ballistics as equation (2) to accurately calculate the radio wave transmission delay.

$$\Delta t_i = \frac{R_i}{C} \tag{2}$$

C is the speed of light. R_i is the distance between the target at the time of t_i and the ground station, Δt is the time delay of the electric wave transmission at t_i which realizes the alignment of the F-frame data. The time code differences of adjacent S-frame of the same F-frame at different stations are all less than the calculation delay, and the S-frame cannot be uniquely aligned.

Literature [2] determines the delay error of the S-frame period through the telemetry equipment indicators and the code rate technical indicators. The S-frame time difference within this range can be considered as the S-frame from the same time, and the maximum utilization of the S-frame is realized. This method relies too much on device index values and fails to solve the actual problems caused by frame loss and error codes.

Table II summarizes and analyzes the existing problems of the real-time alignment algorithm according to the document serial number. At present, the alignment algorithm can complete data alignment with different accuracy, but different alignment algorithms still have corresponding problems. The engineering needs to be further combined with actual needs. Analysis and optimization.

TABLE II. LITERATURE CORRESPONDENCE ALIGNMENT ALGORITHM ANALYSIS

Approach	Problem	Literature number
FA	Frame count errors have a greater impact	[21]
	Cumulative misalignment	[8]
TCMA	The transmission delay of the master station is not considered	[21]
ECA	S-frame time code delay calculation is not resolved	[14]
	Depends on device index value	[2]

IV. POST-MORTEM ALIGNMENT TECHNOLOGY

The post-alignment processing is aimed at the entire telemetry data file record, and the processing process is fine. Researchers pay more attention to post-processing methods. The existing post-alignment methods include: Post-event flag bit alignment (P-FA), post-event time code matching alignment (P-TCMA), post-event error control alignment (P-ECA).

A. P-FA

Compared with the real-time method, it pays more attention to the error correction of the flag bit. The literature [13] uses the time difference of the F-frame (S-frame) frame header divided by the S-frame sampling period to obtain the difference in the number of sub-frames between the F-frames (S-frame count difference).); Starting from the first frame, the frame count is accumulated frame by frame, and the frame count is restored. It overcomes the situation that the frame count and frame data are not one-to-one corresponding to the frame count caused by the clearing of the frame count and the error code. However, when a frame loss occurs in the data record file of one of the measurement stations, the F-frame count difference at the position of the lost frame will increase exponentially, and the alignment algorithm cannot solve the problem of matching the frame data and the frame count at this time.

B. P-TCMA

The focus of P-TCMA is timecode refinement correction. Literature [19] first selects two data streams of the same length, combines the characteristics of the sensor signal, and calculates the delay using the third-order mutual cumulant estimation method. To accurate time delay estimation. Assuming p is the expected maximum delay, Delay D as integer, The measurement signal $y(n)$ is the $AR(p)$ process. The calculation method satisfies:

$$\begin{cases} y(n) = \sum_{i=-p}^{p} a(i)x(n-i) + w(n) \\ a(i) = 0, i \neq D, a(D) = 1 \end{cases} \tag{3}$$

Where $a(i)$ is the coefficient of AR, $w(n)$ is Gaussian white noise, When it is maximum of $|a(i)|$, the i is the required delay. The specific formula is calculated as follows:

$$\begin{cases} c_{yxx}(\tau,\rho) = E\{y(n)x(n+\tau)x(n+\rho)\} \\ c_{xxx}(\tau,\rho) = E\{x(n)x(n+\tau)x(n+\rho)\} \\ c_{yxx}(\tau,\rho) = \sum_{i=-p}^{p} a(i)c_{xxx}(\tau+i,\rho+i) \\ C_{xxx}a = C_{yxx} \end{cases} \tag{4}$$

This method is relatively cumbersome to calculate, the algorithm is difficult to implement, and the time complexity is high, which is not conducive to popularization and application. Literature [18] uses the transmit zero time plus a multiple of the number of data positions to refill the frame time code. As shown in formula: $T_i = T_0 + i * \Delta t$, Where T_0 is the moment when zero occurs. Δt is the number of data positions, T_i is the time corresponding to the data of the first frame. There are three ways to calculate the number of data positions. One is that the program reads the data of the same number of bits to find the corresponding number of data positions based on the same number of bits occupied by the frame data; The difference is divided by the frame period to obtain the number of data positions. I.e. formula $(T_i - T_0)/\Delta t$ .This centralized method reduces the computational complexity of the algorithm, but when frame loss occurs, the problem of the same number of data positions and different data contents has not been resolved. Literature [12] provides a local frame time code correction method, which uses the frame time interval to correct the time code. The specific process is: taking four adjacent frames in the same data recording file, using the principle of "the time difference between adjacent frames is the same", and correcting time codes with different differences. This partial correction method overcomes the problem of frame counting errors, but obviously does not consider the data transmission delay between multiple stations.

C. *P-ECA*

In the A. P-ECA, the calculation of the delay error range is the most critical problem to be solved. The traditional calculation method is to use the difference between the frame time code of the reference station and the time codes of the adjacent frames before and after other stations. Reference [16] sets its size based on the target test model. However, the relevant values are often not given in practice. Reference [10] calculates the current F-frame theoretical time according to formula:

$$T_n = T_0 + (C_n \times P) \tag{5}$$

Among them T_0 is the time zero point, C_n is the frame count value, and P is the frame period. The time delay error range is 20 milliseconds by analyzing the time delay of the time system link and the time difference between the data demodulated by the telemetry station. The calculation of this method relies on the frame count value. When there is a bit error, the theoretical time will be calculated incorrectly, resulting in data loss. Literature [4] determines the allowable error of S-frame sampling according to the code rate technical index, which is used as the time delay error range. Obviously, only the influence of the time difference of the ground station on the data delay is considered, and the transmission delay is not considered. The theoretical trajectory of literature [3] estimates the time delay and corrects the time code as shown in formula, and corrects and number the adjacent F-frame time codes. The F-frame with the same number is the aligned data.

Table III summarizes and analyzes the alignment algorithm after the fact according to the document serial number from the accuracy of the algorithm, the advantages of the algorithm, the existing problems, and whether to consider the transmission delay and frame error. The current alignment algorithm can complete data alignment with different accuracy. , But different alignment algorithms still have corresponding problems, and the engineering needs to be further analyzed and optimized in combination with actual needs.

TABLE III. LITERATURE CORRESPONDENCE ALIGNMENT ALGORITHM ANALYSIS

Approach	Problem	Literature number
P-FA	The problem of matching the frame data and the frame count when the frame is lost is not solved	[13]
	Large amount of calculation, not easy to promote	[19]
P-TCMA	The number of data positions is wrong when the frame is dropped	[18]
	Data transmission delay is not considered	[12]
P-ECA	Depends on device index value	[16]
	Frame count error has not been resolved	[10]
	No consideration of transmission delay	[4]
	Large amount of calculation, not easy to promote	[3]

V. Real-time Optimal Technology

The core of the real-time optimization technology is the QEA. The difficulty of the QEA is to reduce the complexity as much as possible on the premise of ensuring the accuracy of the evaluation. The exploration of the algorithm from selection to F-frame and S-frame marks the inevitable trend of the optimization technology to leap to refinement. The exploration of real-time quality assessment algorithms is the most challenging research problem of real-time data fusion. The existing real-time quality assessment algorithms are based on F-frame and S-frame, which will be described in detail below.

A. Based on F-frame

F-frame QEA (FF-QEA) was proposed and tested in the literature [14]. The specific process is: first check whether the frame time code is continuous and whether the frame synchronization code is correct as the basis for priority selection, then, compare it byte by byte According to the data, the best F-frame is evaluated according to the method selected by the three-judgment principle. Obviously, the system overhead of this method is relatively large, and as the amount of data increases, the problem that the information is too late to process is prone to appear. Moreover, in the process of implementing the three-judgment-two principle, when the three frame byte data in the multi-channel F-frame are all different, the algorithm only relies on the frame synchronization code for quality evaluation, and the accuracy is low.

In order to improve the processing efficiency of the FF-QEA, literature [8] sets a delay buffer window and improves the evaluation strategy. In practical applications, use the frame counter number and sampling correlation value (signal-to-noise ratio) with a small amount of data calculation for quality evaluation, and accurately calculate the buffer size by formula:

$$\frac{L_{FIFO}}{t_r - t_w} > \frac{D}{t_w} \tag{6}$$

L_{FIFO} is the depth of the FIFO buffer, t_w is the bit rate at which data is written to the fusion processing server, t_r is the rate at which the optimal algorithm reads the buffer, and D is the amount of data with the size of the transmission delay. This method effectively reduces the time and space complexity of the algorithm, but when a frame count error occurs, the signal-to-noise ratio alone cannot accurately evaluate the F-frame quality.

B. Based on S-frame

S-frame QEA (SF-QEA) improves the degree of refinement of data processing and maximizes utilization of S-frame. Literature [2] extracts S-frame from the F-frame; prioritizes the algorithm evaluation of S-frame normality, integrity, action period, and characteristic parameters; selects preferred S-frame according to the priority S-frame by S-frame. The algorithm time complexity of this method increases, but it provides a more accurate, reliable and efficient quality evaluation method for the SF-QEA.

Table IV summarizes and analyzes the real-time quality evaluation algorithm according to the document serial number. The current algorithm achieves quality evaluation with different accuracy based on the F-frame and S-frame. The time and resource overhead required for its operation are different. The engineering can be based on different actual conditions. Need to select and improve the appropriate quality assessment algorithm.

TABLE IV. Literature Corresponding QEA Analysis

Approach	Problem	Literature number
FF-QEA	The system overhead is large, and when the amount of data increases, the information is too late to process.	[14]
	Accurate quality evaluation when errors occur in unresolved frame counts	[8]
SF-QEA	Increased algorithm time complexity	[2]

VI. POST-MORTEM OPTIMAL TECHNOLOGY

The ex post selection technology focuses on more accurate quality assessment, which provides a reference for real-time selection. The following is a specific introduction to the post-selection technology based on segment selection (PS- QEA), F-frame (PFF-QEA), and subframe (PSF-QEA).

A. PSF-QEA

PSF-QEA is also known as multi-site selection and splicing method [20] or time reference method [17]. The purpose of algorithm evaluation is to find the connection point of the selection. The specific method is to select the docking point in the critical point (T_1, T_2, T_3) of the measurement area of the ground station and compare and verify the N frames of data before and after. Literature [18] selects two stations to check the following 10 subframes before and after the node: (1) Check whether the frame length meets the predetermined size; (2) Whether the BCD code sequence meets the maximum allowable error range of the sampling period. This method requires a large amount of calculation, and data errors do not affect the frame length, but cause quality misjudgments. Literature [6] puts forward the concept of S-frame loss-of-lock rate [6], that is, the docking point is determined by the S-frame synchronization code error rate in a period of time. As shown in formula: $E = M / N \times 1000‰$, where M is the number of S-frames in the selection, and N is the number of S-frame data synchronization code errors. This method greatly improves the efficiency of selecting butt joints.

B. PFF-QEA

PFF-QEA was first proposed in the literature [20]. Compared with the method of segment selection, it obviously improves the utilization rate of the F-frame data and improves the accuracy of the processing result. However, the actual received data format is changeable, and there are errors and frame loss. The adaptability of this method is relatively poor. The classic quality evaluation method is proposed in [10], that is, the integrity of all subframe synchronization codes in the F-frame is used as the basis for evaluation. This not only guarantees the reliability of the quality assessment, but also improves the calculation efficiency of the quality assessment. Literature [3] uses the classic quality evaluation method, the difference is that a necessity check is performed, as shown in Figure 9: before the quality evaluation, the number of F-frames participating in the evaluation is judged. If there is only one F-frame, select it directly without performing quality evaluation. In this way, under the premise of ensuring the reliability of the algorithm, the calculation amount of the algorithm is reduced.

C. PSF-QEA

Literature [5] uses 3 kinds of constraint conditions to select the F-frame, and the F-frame that meets the constraint conditions will be determined as qualified. The constraints are calculated as follows:

$$\begin{cases} \left| T_{ki} - T_j^g \right| < \varepsilon \\ C_j^g = C_{ki} + \Delta C \\ C_{ki} = C_{k(i-1)} + 1 \end{cases} \tag{7}$$

k is the station number, T_{ki} is the F-frame BCD time code, T_j^g is the F-frame BCD time code of the j-th period, ε is allowable error for F-frame header time, C_j^g is the global frame count after the j-th period is corrected, C_{ki} is frame count of the i-th F-frame, ΔC is the correction value caused by frame count overflow or clearing, $C_{k(i-1)}$ is the frame count for the i-1th F-frame. This algorithm has high requirements for data preprocessing, discarding incomplete F-frame data, which is not conducive to full use of data. The S-frame-based post-mortem quality evaluation algorithm is characterized by a high degree of refinement and a large computational complexity. Literature [11] formatted the S-frame data as shown in the formula:

$$D = \left(T, a, A, F^{'} \right) \tag{8}$$

The T vector represents the time code, the a vector represents the S-frame data, the A vector represents the S-frame synchronization code, and the F represents the identifier; the quality evaluation method is as follows:

a) Check calculation for subframe structure: F data frame error evaluation value is 1, the synchronization code is normal synchronization code is 0, the synchronization code is inverted code is -1, and its value is assigned to the structure check vector value of δ_1;

b) Check the subframe count: the difference between the frame counts is 1, and the frame count check evaluation value is 1, otherwise it is 0. Assign the evaluation value in the entire matrix to the frame count check vector of δ_2;

c) S-frame time code verification: the time code difference between adjacent S-frames is 0 within the allowable error range of the time code; otherwise, it is 1. The verification result is recorded as a vector of δ_3;

d) Inverted code period check: the length between the positions where adjacent inverted codes appear is equal to the length of the whole frame, which is 0, otherwise it is unqualified and its value is 1. The inverted code period check result is recorded as a vector of δ_4;

e) Quality evaluation value: assign weight to the above four check vectors (w_1, w_2, w_3, w_4), Calculate the overall evaluation value. As shown in the formula:

$$\delta = w_i \bullet \delta_{ij} \tag{9}$$

The literature [7] evaluates the S-frame quality based on the principle of nearest neighbor clustering. The better the S-frame quality is mapped to the higher the similarity, the closer the distance from the cluster center. First, the S-frame data at the same time is subjected to a standardized metric value to reflect the degree of dispersion of the S-frame data, that is, the standard metric value formula is obtained by the average value of the absolute deviation:

$$\begin{cases} S_{vi} = \dfrac{1}{N}\sum_{n-1}^{N}\left|v_n^i - m_{vi}\right| \\ Z_{vi}^n = \dfrac{v_n^i - m_{vi}}{S_{vi}}(n = 1, 2, \cdots, N) \end{cases} \tag{10}$$

Among them, i is the station number, and N is the length of the subframe. Then calculate the Manhattan distance of the normalized metric of the subframe data:

$$d_{ij} = \sum_{n-1}^{N}\left|v_n^j - v_n^i\right| \tag{11}$$

d_{ij} is the difference value of the S-frame data between station i and station j. Finally, set the cluster center radius, classify the corresponding S-frame data, and select the S-frame closest to the cluster center as the optimal result. This similarity-based method provides a new idea for the quality evaluation algorithm, which is worthy of attention and in-depth study by researchers.

Table V summarizes and analyzes the real-time and post-event quality evaluation algorithms according to the document number. Among them, the complexity of the algorithm principle and the accuracy of the algorithm processing results include 5 levels from high to low, high, normal, low, and low. The resource overhead used by the algorithm is divided into large, large, general, small, and small from large to small. The current algorithm achieves quality evaluation with different accuracy based on selection, F-frame, and subframe. The time and resource overhead required for its operation are different. In engineering, suitable quality evaluation algorithms can be selected and improved according to different actual needs.

TABLE V. LITERATURE CORRESPONDENCE ALGORITHM ANALYSIS TABLE

Approach	Problem	Literature number
PSF-QEA	Data error does not affect the frame length, causing quality misjudgment.	[18]
	To solve the judgment error caused by dropped frames	[6]

PFF-QEA	Unsolved the problem of different comparison results caused by dropped frames and errors	[20]
	The assessment basis is relatively simple	[10]
	Not given due to frame loss	[3]
	Data preprocessing requirements are high, and the incomplete F-frame data is discarded, which is not conducive to the full use of data.	[5]
PSF-QEA	The calculation is cumbersome and not easy to promote	[11]
	Cluster center radius is not easy to choose	[6]

VII. SHORTCOMINGS AND PROSPECTS OF EXISTING METHODS

At present, it is difficult for fusion technology to take into account the intricacies of the actual situation at the same time. The research on generalized, high-efficiency, and high-precision processing methods for data fusion has increased the difficulty, and there are problems that need to be further studied and improved.

Data frame loss is an inevitable interference factor that affects fusion accuracy, and is a key issue faced by alignment and optimization algorithms. Once frame loss occurs, the algorithm will run delayed alignment, wrong alignment, and invalid selection. It will definitely affect the calculation time and accuracy of the fusion result. Researchers use a method based on pseudo-S-frames (PS-frame) to fill in the missing frame data and solve the related difficulties of the alignment technology [7]. However, there are few frame parameters in the PS-frame, which are quite different from the actual frame signal, and when participating in the optimization, the accuracy of the resultant data is reduced. In subsequent research, the method of pattern recognition and parameter estimation can be used to predict the S-frame data [25], so that the data participating in the selection is closer to the actual value.

The design of the key algorithms for alignment and optimization in the fusion technology mainly uses specific parameters such as frame count, time code, synchronization word, and the phenomenon of bit errors in this part of the data is bound to have a certain impact on the operation of the algorithm, especially for those that rely too much on specific parameters [21]. Algorithms are often fatal. Although fusion processing uses related technologies to repair specific parameters [3], the repair method will also fail when encountering more complex situations. Therefore, in the selection technique, researchers try to measure the similarity by calculating the Manhattan distance metric based on the standard metric value of the entire frame of data to achieve the purpose of selection [8]. Based on this idea, we can learn from the machine learning method for time series data mining technology [23, 24], accurately calculate the similarity, and match the entire frame of data to achieve the purpose of fusion.

VIII. CONCLUSION

Continuously improving the key algorithms of the fusion technology in practice is an effective way to ensure the accuracy and reliability of the test data. The study introduced the structural characteristics of telemetry data and the information processing flow, analyzed the actual problems of transmission delay and frame loss and error encountered in data processing, and pointed out the technical difficulties in data fusion. Starting from actual engineering requirements and technical points, the development process of real-time alignment and selection is explained, and the alignment algorithms and QEA involved are classified and analyzed in detail. According to the shortcomings of the existing methods, the next step of the algorithm will focus on the direction of frame loss prediction and the matching of the whole frame, and design pattern recognition and machine learning algorithms to improve the accuracy of the fusion process. With the continuous advancement of computer technology, real-time data fusion technology is bound to burst into new vitality.

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靶场遥测数据实时融合技术研究

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***摘要—*遥测数据是地面站获取飞行器系统工作状态和环境参数的重要数据资料，其融合处理是对多路数据进行择优筛选，提高全程记录可靠性和准确性的关键技术。由于遥测数据量较大，传输过程存在时延误差，并伴随丢帧和误码的现象，为数据融合的对齐和选优带来了严峻挑战。研究从融合技术的应用背景出发，介绍并分析了遥测数据的特点及融合技术的难点；概述目前对齐、选优的相关研究成果以及发展历程，根据工程需求和技术要点，分别从实时和事后的角度出发，对其中涉及的对齐算法、质量评估算法进行了详细的分类、分析；最后，归纳总结了现有方法的不足，展望未来发展的方向，以此为相关研究者提供参考。**

关键词-遥测数据; 数据融合; 对齐; 选优

1. 介绍

遥测系统是现代飞机和航空武器发射试验中的重要内容[1]。多年来，随着试验任务之间的不断磨合和改进，形成了一套基于多站测控的遥测数据处理流程[5]。数据融合作为处理流程中的关键技术，主要通过对各站接收的多路数据进行择优筛选，以提高全程记录可靠性和准确性[3, 4]。

融合技术的传统方法是事后人工统计一段数据的出错情况，择优进行拼接[19]。基于遥测/计算机系统的发展，2009 年徐洪洲等人基于“三判二原则”，全帧数据逐字节对比算法，实现了融合技术的自动化处理。用时，也暴漏出了处理过程中存在的传输时延、丢帧、误码等一系列问题。基于文献[17]建立标准、统一的数据量化方法。2014 年，刘桂生等人利用理论弹道刻画了数据传输时延，并且，将融合技术分为了对齐和选优两部分进行研究。, 之后融合技术领域的各种算法相继被提出[7-17]，旨在克服实际任务中遇到的难题，向着更加通用、高效、精准的方向不断发展。

目前，对于融合技术的研究已经取得较多成果，但研究内容相对分散、不成体系。因此，研究从数据融合主要涉及的对齐、选优两个部分出发，归纳总结实时和事后融合处理方法的研究现状，并对其中涉及的关键算法进行阐述。力求为数据融合处理技术的发展提供可行的研究思路。

2. 遥测数据

遥测数据通常使用 PCM 体制进行测量，采样周期为毫秒级。采集同一周期内的参数作为一帧 PCM 数据流，经过一定的时间间隔再次采集，循环往复形成最终的 PCM 遥测数据流，记录在表 1 所示的二进制数据流文件中，其数据量较为庞大。

遥测数据的处理流程如图 1 所示，各地面测站将接收的密文数据实时发送到指控中心。先经过解密预处理设备以及解密器并行独立完成数据密，并输出明文数据；再经过数据融合处理服务器，多路明文数据剪辑拼成一条最优的全程数据流；最后，中心计算机系统对全程测量数据流进行参数分路并计算处理和结果供显示。

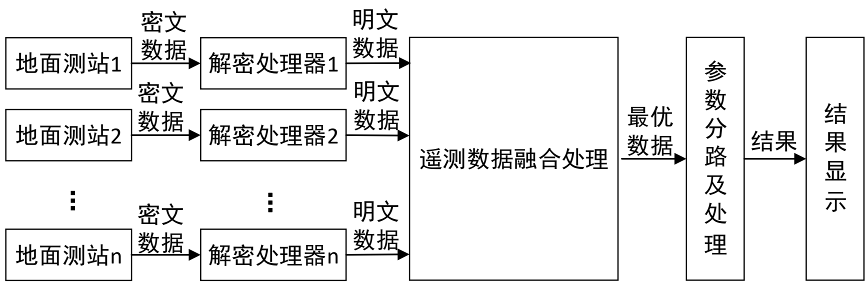

图 1 数据处理流程图

数据融合处理中，受测站空间地理位置的影响，目标同一时刻发送的数据解析到融合处理服务器的时刻不同，即传输时延。因此，数据融合的第一要务是对齐操作，匹配不同地面测站接收目标发出的同源帧数据。对齐的难点主要在于，目标飞行中与测站的距离实时动态变化引起传输时延的变化以及数据传输过程中可能出现的丢帧误码现象等。对齐之后，需要筛选记录质量较好的部分，完成全程数据的拼接，称为选优。而选优的关键，是如何对不同测站的同源帧进行准确的质量评估。

综上所述，遥测数据的数据量庞大，信息处理流程繁琐，且伴随丢帧误码以及传输时延。数据对齐、选优处理面临的问题错综复杂，并且算法稍有延时，将出现累积等待现象，融合时间成倍增加，这无疑给融合技术的对齐、选优带来了严峻挑战。

3. 实时对齐技术

实时对齐处理必须对当前接收的有限帧数据做出及时判断、选择，对齐方法实时性、可靠性要求高。实时对齐往往较为粗略，主要包括实时标志位对齐、实时时码匹配对齐和实时误差控制对齐。

3.1 *实时标志位对齐*

实时标志位对齐中最经典的算法是文献[21]中提出的基于帧计数的对齐方法。帧计数属于遥测参数的一部分,同时具备连续性和统一性，并且其计算量相对较小，算法时间复杂度相对较低，成为实时对齐技术的首选。但帧计数误码对算法来说是致命的。

文献[8]优化了接收缓冲区以及帧计数误码时的判决条件，降低了计算机资源的使用，当其出现帧计数不一致时，选择帧计数较小一路作为对齐结果数据。 然而，多路数据连续出现帧计数误码时，这种方法会导致融合结果出现累积的帧计数错误，如表 1 所示，测站 A 的 1，4 号帧计数产生误码，测站 B 帧计数连续误码，包括 2，3，4 号数据帧，采用帧计数对齐时，融合结果为 28586、65467、65356、65523 的累积错误。

表 1 累积错误对齐过程表

帧序号	测站 A	测站 B	融合结果	正确
1	28586	65530	28586	65530
2	65531	65467	65467	65531
3	65532	65356	65356	65532
4	65523	65533	65523	65533

3.2 *实时时码匹配对齐*

实时时码匹配对齐首先进行时码修正，然后利用时码匹配对齐子帧或全帧。文献[21]参照主站帧的时码对其他测站进行修正。这种方法便于实现，但由于未考虑主站时码在数据传输过程中存在的时延问题，数据对齐结果时间精度有所损失。

3.3 *实时误差控制对齐*

实时误差控制对齐的主要思路是计算帧数据传输过程中的时间误差范围，称为时延误差范围。以任意测站帧时码为基准，处于时延误差范围内的帧时码对应数据确定为同一时刻的帧。如公式（1）所示：

$$T+\Delta t>T>T-\Delta t \tag{1}$$

T 为基准时间，Δt 为时延误差范围。

文献[14]利用理论弹道如式（2），精确计算电波传输时延。

$$\Delta t_i=\frac{R_i}{C} \tag{2}$$

C 为光速；R_i 为 t_i 时刻目标与地面测站的距离；Δt 为 t_i 时刻电波传输延时，实现了全帧数据的对齐。不同测站同一全帧的相邻子帧时码差值均小于计算时延，未能唯一地对齐子帧数据。

文献[2]通过遥测设备指标及码速率技术指标确定子帧周期的延时误差，子帧时差在这一范围内可认为是来自同一时间的子帧，实现了子帧数据的最大化利用。这种方法过于依赖设备指标值，且未能解决丢帧误码带来的实际问题。

表 2 对实时对齐算法按照文献序号对现有实时对齐方法进行了汇总分析。

表 2 实时对齐算法统计表

处理方法	问题	文献编号
实时标志位对齐	帧计数误码影响较大	[21]
	累积错误	[8]
实时时码匹配对齐	未考虑主站传输时延	[21]
实时误差控制对齐	子帧时码延时计算未解决	[14]
	依赖设备指标值	[2]

4. 事后对齐技术

事后对齐处理针对的是全程遥测数据文记录件，处理过程精细。研究者多关注于事后处理的方法，现有的事后对齐方法有事后标志位对齐、事后时码匹配对齐和事后误差控制对齐。

4.1 *事后标志位对齐*

事后标志位对齐相比实时方法更加注重标志位的误码修复，文献[13]利用全帧（副帧）帧头时间差除以子帧采样周期，得到全帧之间的子帧个数差（子帧计数差）；再从首帧开始，逐帧进行帧计数累加，进行帧计数修复。克服了帧计数清零及误码带来的帧计数与帧数据不一一对应的情况。但当其中一台测站的数据记录文件中发生丢帧时，丢帧位置的子帧计数差将成倍增加，对齐算法未能解决此时帧数据与帧计数的匹配问题。

4.2 *事后时码匹配对齐*

事后时码匹配对齐的重点是时码精细化修正。文献[19]首先选取两段相同长度的数据流，结合传感器信号特点，利用 3 阶互累积量估计的方法计算延时，旨在充分利用现有数据之间相互关联以及充分考虑传感器噪声，做到精确时延估计。假设 p 为期望的最大时延，延迟 D 为整数，测量信号 $y(n)$ 为 $AR(p)$ 过程。如公式（3）所示：

$$\begin{cases} y(n)=\sum_{i=-p}^{p}a(i)x(n-i)+w(n) \\ a(i)=0,i\neq D,a(D)=1 \end{cases} \tag{3}$$

其中 $a(i)$ 为 AR 系数，$a(i)=0, i\neq D, a(D)=1$，$w(n)$ 是高斯白噪声。延时估计的计算过程是将（3）式代入（4）式和（5）式中，得到（6）式，对于不同的 (τ,ρ)，获得（7）式的线性方程组，当 $|a(i)|$ 最大时，i 即为所求的时延。具体的公式计算如下：

$$\begin{cases} c_{yxx}(\tau,\rho)=E\{y(n)x(n+\tau)x(n+\rho)\} \\ c_{xxx}(\tau,\rho)=E\{x(n)x(n+\tau)x(n+\rho)\} \\ c_{yxx}(\tau,\rho)=\sum_{i=-p}^{p} a(i)c_{xxx}(\tau+i,\rho+i) \\ C_{xxx}a=C_{yxx} \end{cases} \tag{4}$$

这种方法计算相对繁琐，算法实现的难度较大，时间复杂度较高，不利于推广应用。文献[18]使用发射零点时刻加上数据位置数的倍数对帧时码进行重新填补。如公所示：$T_i=T_0+i*\Delta t$，式中 T_0 为发生零点的时刻。Δt 对于数据位置数，T_i 即为第 i 帧数据对应的时刻。对于数据位置数，有三种方法计算方法，其一，根据帧数据所占的位数相同，程序读取相同位数的数据求出对应的数据位置数；其二，利用数据时刻与发射零点的差值除以帧周期取得数据位置数。即公式 $(T_i-T_0)/\Delta t$。这种集中方法降低了算法的计算量，但当发生丢帧时，数据位置数相同数据内容不同的问题尚未解决。文献[12]中给出了一种局部帧时码修正方法，即利用帧时间间隔修正时码。具体的过程为：取同一数据记录文件中相邻四帧，采用“相邻帧时间差相同”的原理，修正存在差值不同的时码。这种局部修正方法，克服了帧计数发生误码的问题，但显然没有考虑多个测站之间到数据传输时延。

4.3 *事后误差控制对齐*

事后误差控制对齐中，时延误差范围计算是需要解决的最关键的问题。传统的计算方法是利用基准测站帧时码与其他测站前后临近帧时码的差值得出。文献[16]根目标试验型号设置其大小。但实际中往往并未给出相关数值。文献[10]根据式（5）计算当前全帧理论时间：

$$T_n=T_0+(C_n\times P) \tag{5}$$

其中 T_0 为时间零点，C_n 为帧计数值，P 为帧周期。时延误差范围通过分析时统链路的延时和遥测站解调数据的时间差为±20 毫秒。这种方法计算时依赖帧计数值，当其出现误码时，理论时间将计算出错，造成数据缺失。文献[4]根据码速率技术指标确定子帧采样的允许误差，以此作为时延误差范围。显然仅考虑了地面测站的时间差异对数据延时的影响，而未考虑传输时延。文献[3]理论弹道，如式（2）所示估算时延、修正时码，并将相邻对全帧时码进行了修正并编号，相同编号的全帧即为对齐后的数据。

表 3 对事后的对齐算法按照文献序号从存在的问题进行了汇总分析。

表 3 事后对齐算法统计表

处理方法	问题	文献编号
事后标志位对齐	未解决丢帧时的帧数据与帧计数的匹配问题	[13]
	计算量大，不易于推广	[19]
事后时码匹配对齐	丢帧时数据位置数出错	[18]
	未考虑数据传输时延	[12]
事后误差控制对齐	依赖设备指标值	[16]
	帧计数误码尚未解决	[10]
	未考虑传输时延	[4]
	计算量较大，不易于推广	[3]

5. 实时选优技术

选优技术的核心是质量评估算法。质量评估算法的难点是保证评估准确性的前提下尽可能降低复杂程度。算法从选段到全帧和子帧的探索，标志着选优技术向精细化跨越的必然趋势。实时质量评估算法的探索，是数据实时融合最具有挑战性的研究问题。现有的实时质量评估算法基于全帧和子帧，下面进行具体的详细介绍。

5.1 *基于全帧*

基于全帧的实时质量评估算法是由文献[14]提出并进行试验，具体的过程为：首先检查帧时码是否连续，帧同步码是否正确作为优先级选择的依据；然后，逐字节比较数据，按照次数最多相同的数据，即三判二原则选定的方法评定出最优的全帧。显然，这种方法系统开销较大，随着数据量的增大，容易出现信息来不及处理的问题。并且，在执行三判二原则过程中，当多路全帧中三个帧字节数据均不相同的时，算法仅靠帧同步码进行质量评估，准确度较小。

为了提高算法的处理效率，文献[8] 设置了时延缓存窗口并改善了评估策略。在实际应用中，使用数据计算量较小的帧计数字和采样相关值（信噪比）进行质量评估；并通过公式（6）精确计算缓冲区大小：

$$\frac{L_{FIFO}}{t_r - t_w} > \frac{D}{t_w} \tag{6}$$

其中 L_{FIFO} 为 FIFO 缓冲区的深度，t_w 为数据写入融合处理服务器的位速率，t_r 为选优算法读取缓冲区的速率，D 为传输时延大小时间的数据量。这种方法有效降低了算法的时间和空间复杂度，但当帧计数出现误码时，仅靠信噪比不能准确进行全帧质量评估。

5.2 *基于子帧*

基于子帧的实时质量评估提高了数据处理的精细化程度，子帧数据得到最大化利用。文献[1]从全帧中进行子帧提取；通过对子帧数据规范性、完整性、作用时段以及特征参数的算法评估进行优先级排序；逐子帧对照优先级进行择优选取子帧。这种方法的算法时间复杂度 2 增加了，但为基于子帧的实时质量评估算法提供了更加精准、可靠且高效的质量评判方法。

表 4 对实时选优算按照文献序号从存在的问题进行了汇总分析，目前选优算法在不同精度上可以完成数据选优，但不同的选优算法仍然存在相对应的问题，工程上需要进一步结合实际需求进行分析优化。

表 4 实时选优算法统计表

处理方法	问题	文献编号
基于全帧的实时质量评估算法	系统开销大，数据量增大时，信息来不及处理	[14]
	未解决帧计数出现误码时的精确质量评估	[8]
基于子帧的实时质量评估算法	算法时间复杂度增加	[2]

6. 事后选优技术

事后选优技术关注的是更为精准的质量评估，这为实时选优提供了借鉴的依据。下面对基于选段、基于全帧、基于子帧的事后选优技术进行具体介绍。

6.1 *基于选段*

基于选段的事后质量评估算法，又称为多站位选段拼接法[20]或时间基准法[17]。算法评估的目的是找出选段对接点。具体的做法是在地面测站测量区临界点 (T_1, T_2, T_3) 中选取对接点并前后 N 帧数据进行对比校验。文献[17]选取两站对节点前后 10 条子帧，进行如下检查：（1）检查帧长度是否符合既定大小；（2）BCD 码顺序是否符合采样周期最大允许误差范围。这种方法的计算量较大，且数据误码并不影响帧长度，反而造成质量误判。文献[6] 提出了子帧失锁率[5]的概念，即通过一段时间中子帧同步码错误率确定对接点。如式所示：$E = M / N \times 1000‰$，其中，M 为选段中的子帧个数，N 为子帧数据同步码错误的个数。这种方法大大提高了选定对接点的效率。

6.2 *基于全帧*

基于全帧的事后质量评估算法是文献[19]首次提出的，该算法采用逐字节三判二原则的方法进行计算。相对选段的方法，显然提高了全帧数据的利用率，提升了处理结果的准确性。然而实际接收的数据格式多变, 且存在误码、丢帧的情况,该方法的适应能力相对较差。经典的质量评估方法是文献[10]提出的，即利用全帧中的所有子帧同步码完整性作为评估的依据。既保证了质量评估的可靠性，又提高了质量评估的计算效率。文献[3]使用经典质量评估方法，不同的是，进行了必要性检查，在质量

评估之前，判断参加评估的全帧个数。如果仅有一条全帧则直接选定，不进行质量评估。这样在保证算法可靠性的前提下，降低了算法的计算量。

文献[5] 使用 3 种约束条件对全帧进行遴选，符合约束条件的全帧将被确定为质量合格。约束的计算如下：

$$\begin{cases} \left|T_{ki}-T_j^g\right|<\varepsilon \\ C_j^g=C_{ki}+\Delta C \\ C_{ki}=C_{k(i-1)}+1 \end{cases} \tag{7}$$

其中， k 为测站序号，T_{ki} 为全帧 BCD 时码，T_j^g 为第 j 个周期的全帧 BCD 时码，ε 为全帧帧头时间允许误差；C_j^g 为第 j 周期修正后全局帧计数，C_{ki} 第 i 个全帧的帧计数，ΔC 为帧计数溢出或清零导致的修正值； $C_{k(i-1)}$ 为第 i-1 全帧的帧计数。这种算法对数据预处理要求较高，丢弃残缺的全帧数据，不利于数据的充分利用。

6.3 *基于子帧*

基于子帧的事后质量评估算法的特点是结果精细化程度高，计算复杂度大。文献[10]将子帧数据进行如式 8 所示的格式化处理：

$$D=\left(T,a,A,F^{'}\right) \tag{8}$$

式中 T 向量代表时码，a 向量代表子帧数据，A 向量代表子帧同步码，F 代表标识字；质量评估的方法如下：

6.3.1 对子帧结构校验计算：F 数据帧错误评估值取为1，同步码为正常同步码取值为0，同步码为反码取值为-1，将其值赋给结构校验向量值 δ_1；

6.3.2 对子帧计数校验：帧计数之间的差值为 1，帧计数校验评估值为 1，否则为 0。将整个矩阵中的评估值赋给帧计数校验向量δ_2；

6.3.3 子帧时码校验：相邻子帧时码差值介于时码允许误差范围内为 0，否则为 1。校验结果记为向量δ_3；

6.3.4 反码周期校验：相邻反码出现的位置之间的长度等于全帧长度为0，否则为不合格其值为 1.反码周期校验结果记为向量 δ_4；

6.3.5 质量评估值：将以上四个校验向量赋予权重$\left(w_1,w_2,w_3,w_4\right)$，计算总体评估值。如式 17 所示：

$$\delta=w_i\bullet\delta_{ij} \tag{9}$$

文献[7]子帧质量评估的依据最近邻聚类实现原理，将子帧质量越好映射为相似度越高，距离聚类中心的距离越近。首先将同一时刻子帧数据进行标准化度量值，用来反映子帧数据的离散程度，即通过绝对偏差的平均值求出标准度量值式：

$$\begin{cases} S_{vi}=\dfrac{1}{N}\displaystyle\sum_{n-1}^{N}\left|v_n^i-m_{vi}\right| \\ Z_{vi}^n=\dfrac{v_n^i-m_{vi}}{S_{vi}}(n=1,2,\cdots,N) \end{cases} \tag{10}$$

其中，i 为站位编号，N 为子帧长度。然后计算子帧数据标准化度量值的曼哈顿距离：

$$d_{ij}=\sum_{n-1}^{N}\left|v_n^j-v_n^i\right| \tag{11}$$

式中 d_{ij} 是测站 i 和测站 j 之间的子帧数据相异度值。最后，设置聚类中心半径，将对应的子帧数据进行分类，并选取距离聚类中心最近的子帧为最优结果。这种基于相似度的方法为质量评估算法提供了一种新的思路，值得研究人员关注和深入研究。

表 5 对事后的选优算法按照文献序号进行了汇总分析.目前算法基于选段、全帧、子帧达到了不同精度的质量评估，其运行需要的时间以及资源开销各不相同，工程上可根据不同的实际需求选择并改进合适的质量评估算法。

表 5 事后选优算法统计表

处理方法	问题	文献编号
基于选段的事后质量评估算法	数据误码并不影响帧长度，造成质量误判。	[18]
	为解决丢帧引起的评判失误	[6]
基于全帧的事后质量评估算法	未解决丢帧误码引起的对比结果均不相同的问题	[20]
	评估依据较为单一	[10]
	未给出丢帧引起的	[3]
	数据预处理要求较高，丢弃残缺的全帧数据，不利于数据的充分利用。	[5]
基于子帧的事后质量评估算法	计算繁琐，不易推广	[11]
	聚类中心半径不易选取	[6]

7. 现有方法的不足与展望

目前，融合技术在面临错综复杂的实际情况中很难同时兼顾，常常顾此失彼。对开展数据融合通用化、高效率、高精度处理方法的研究增加了难度，存在需要进一步研究和完善的问题。

数据丢帧是影响融合精度不可避免的干扰因素，是对齐、选优算法主要面临的关键问题。一旦发生丢帧，算法运行将出现延时对齐、错误对齐以及无效选优等。必将影响融合结果的计算时间和精度。研究人员使用基于伪子帧的方法，补齐丢失的帧数据，解决了对齐技术的相关难点[7]。然而，伪子帧中帧参数较少，与实际帧信号相差较大，参与选优时，降低了结果数据的精度。在后续的研究中，可以采用模式识别和参数估计的方法对子帧数据进行预测，使得参与选优的数据更加接近实际的数值。

融合技术中对齐、选优关键算法的设计主要利用帧计数、时码、同步字等特定参数，而这部分数据产生误码的现象势必对算法运行产生一定的影响，尤其对过于依赖特定参数的算法来说[21]，常常是致命的。虽然融合处理使用相关技术对特定参数进行修复，然而当遇到更为复杂的情况时，修复方法也将失效。因此，选优技术中，研究者试图通过整帧数据的标准度量值计算曼哈顿距离度量进行相似度衡量，达到选优的目的[8]。基于这种思想，可借鉴机器学习方法对时间序列的数据挖掘技术[23,24]，精确计算相似度，对整帧数据进行匹配，达到融合的目的。

8. 结论

实践中不断完善融合技术关键算法，是保证试验数据准确可靠的有效途径。研究介绍了遥测数据的结构特点以及信息处理流程，分析数据处理中遇到的传输时延和丢帧误码的实际问题，指出数据融合中的技术难点。从实际工程需求以及技术要点出发，阐述对齐、选优的发展历程，对其中涉及的实时和事后对齐和质量评估算法进行了详细的分类、分析。根据现有方法存在的不足，下一步算法将针对丢帧预测与整帧匹配的方向展开研究，设计模式识别和机器学习算法提高融合处理的精度。随着计算机技术的不断进步，数据融合技术必将迸发出新的活力。

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