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An investigation of collisions between fiber positioning units in LAMOST

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Abstract The arrangement of fiber positioning units in the LAMOST focal plane may lead to collisions during the fiber allocation process. To avoid these collisions, a software-based protection system has to abandon some targets located in the overlapping field of adjacent fiber units. In this paper, we first analyze the probability of collisions between fibers and infer their possible reasons. It is useful to solve the problem of collision handling system is designed by using a master-slave control structure between the micro control unit and microcomputer. Simulated experiments validate that the system can provide real-time inspection and swap information between the fiber unit controllers and the main controller.

Key words: methods: statistical — telescopes — instrumentation: detectors — methods: data analysis — methods: observational

1 INTRODUCTION

The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST), which is also called the Guo Shou Jing Telescope, is a special reflecting Schmidt telescope with a large aperture and wide field of view. The available large focal surface accommodates up to 4000 fibers, by which the collected light of distant and faint celestial objects down to 20.5 magnitude is fed into the spectrographs, promising a very high spectral acquisition rate of several tens of thousands of spectra per night (Cui et al. 2012; Chen et al. 2014).

The focal surface of the telescope, which has a diameter of 1.75 m, is divided into 4000 individual domains as shown in Figure 1. The diameter of each fiber is 33 mm and the distance between two adjacent units is 25.6 mm, so the overlapping domain will appear in the observed field of every two adjacent fiber units (Cui et al. 2012). Therefore, the fiber arrangement can efficiently avoid blind areas in the fields of view (FoVs). At the same time, the positioning procedure of the relevant fiber units may also be confused when targets are allocated to the overlapping field. On the other hand, each unit is driven by two stepper motors (Xing et al. 1998), the design of which can be seen in Figure 2. The unit contains a central shaft which revolves around its fixed end in a range of $\pm 180^{\circ}$, and an off-center shaft which revolves around its end that is connected to the free end of the central shaft at $\pm 90^{\circ}$ (Li et al. 2000). In theory, mechanical collisions among the fiber positioning units can be avoided by the Survey Strategy System of LAMOST which must discard potential objects.

In this study, we first analyze the probability of collisions among fibers by utilizing a binomial probability distribution. Then, we infer several related reasons for losing targets during an observation. Based on this, a collision handling system is designed by using a master-slave control structure between a micro control unit (MCU) and a microcomputer. In order to validate its usefulness and correctness, simulated experiments are designed and the neighbors of seven fiber positioning units are considered.

This paper is organized as follows. In Section 2, we analyze the collision probability of an overlapping area associated with fiber units. Additionally, we explore the possible reasons for not being able to acquire objects during the survey. The design of the hardware collision handling system is detailed in Section 3. The results and discussions are summarized in Section 4.

2 MECHANICAL COLLISIONS BETWEEN FIBER POSITIONING UNITS

2.1 The Fiber Allocation Rate

In a dense, multi-fiber distribution system, the allocation rate of the fibers should be taken into account. Assuming that the distribution of objects in the focal surface of LAMOST is uniform, the probability (p) of an object in a certain domain equals the ratio of the area in the domain to that of the entire focal surface (Peng et al. 2003). The probability distribution for targets follows a binomial distribution which is expressed in Equation (1).

$$p(K,N) = C_N^K p^K (1-p)^{(N-K)},$$
(1)



Fig.1 The distribution of fiber-positioning units in the focal plane (Cui et al. 2012).



Fig. 2 Double revolving fiber-positioning unit (Cui et al. 2012).

where N is the number of objects in the FoV and K is the number of objects in a domain.

2.1.1 The collision probability of two objects in the overlapping area of adjacent fiber units

Assuming that any pair of adjacent units is independent of others, and each fiber unit has six neighbors, we estimate that about 11 630 pairs of units are in the LAMOST fiber plate. A mechanical collision may happen in an overlapping region (S_o) as shown in Figure 3, since a fiber cannot aim at targets inside the structure of the fiber positioningunit. In Figure 3, let x be a target in S_o . S_x is the circular domain whose center is x and radius is 4.5 mm. A collision will occur when target y falls in S_x . Thus, the collision probability of two fibers in an overlapping area obeys the binomial distribution described in Equation (2).

$$p = C_N^2 p_{s_0}^2 (1 - p_{s_0})^{N-2} (1 - p_{s_{\text{non}}})^N p_{s_x}, \qquad (2)$$

where $C_N^2 p_{S_o}^2 (1 - p_{S_o})^{N-2}$ is the probability of only one object being in the overlapped region S_o , $C_N^0 (1 - p_{S_{non}})^N$ is the probability of no objects being in S_{non} , and p_{S_x} is the probability under the condition of only two objects in the overlapped region of adjacent fiber units. We calculate



Fig. 3 Divided domains in a pair of fiber units. In this figure, S_{\circ} represents the overlapping region, S_{non} is the non-overlapping area, x and y are two targets, and S_x is a circular area defined by the center x and radius 4.5 mm.



Fig.4 The collision probability p changes with N (the number of objects). The red curve is the variation tendency of p when the radius of S_x is 6 mm and the blue curve is that when the radius is 4.5 mm.

this probability for different numbers of targets listed in Table 1.

The probability curve for the two target collision in the overlapped region is p, and how p changes with N (for various number of objects) is plotted in Figure 4. The red curve demonstrates how p changes with N when the radius of S_x is 6 mm and the blue curve that when the radius is 4.5 mm. 4.5 mm is just the theoretical radius of S_x , yet the radius is slightly larger than the theoretical one in practice. So, we also consider 6 mm to be the radius of S_x in the probability calculation, which would be a more reasonable value. In the curve shown in Figure 4, we see that the collision probability p reaches a peak at about 3500, which is close to the desired number of targets (except for a few of the skylight fiber units) in each observation. It is necessary to handle these collisions.

2.1.2 The collision probability of more objects in an overlapping area

The collision probability caused by more than two objects being allocated in the collision areas is relatively small. In case there are only three objects in $S_{\rm o}$, the collision probability is defined by Equation (3) and its value is shown in Table 1.

$$p = C_N^3 p_{S_0}^3 (1 - p_{S_0})^{N-3} (1 - p_{S_{\text{non}}})^N p_{S_{xy}}, \quad (3)$$

where S_{xy} is the domain that is defined by two objects x and y, which is described by Equation (4) and shown by the hatched part of Figure 3.

$$S_{xy} = \frac{\int_0^{4.5} \frac{2[\frac{\theta \pi r^2}{2\pi} - (r/2)\sin(\theta/2)l]2\pi l}{S_o} dl}{\int_0^{4.5} 2\pi l dl},$$
 (4)

where $l \in [0, 4.5]$ is the range of distances between objects x and y, and r is the radius 4.5 mm. Then the average area of S_{xy} is 19.6539 mm² and the ratio of the possible collision zone in the fiber focal plane is $p_{S_{xy}}$.

Generally, the total collision probability of any pair of fiber positioning units is defined by Equation (5).

$$p = \sum_{j=2}^{N} C_{N}^{j} p_{S_{0}}^{j} (1 - p_{S_{0}})^{N-j} (1 - p_{S_{non}})^{N} p_{S_{xy...j}}.$$
 (5)

In fact, ~11630 pairs of fiber-positioning units are located in the focal plane of LAMOST. We select several groups of input target numbers and calculate the relevant collision probability for the radii of 4.5 mm and 6 mm. Table 1 lists the result for p_{Sx} , p_{Sxy} , n_{Sx} , n_{Sxy} and $\Sigma(n_{Sx}, n_{Sxy})$. It suggests that the number of lost objects tends to reach a maximum when the number of input targets in the FoV is about 3500. The total amount of lost targets can reach a hundred, therefore it is necessary to reacquire the lost targets by considering the design of the LAMOST survey.

2.2 Discussion

The collision probability reflects that the rate of loss from collision which may reach about 3%. However, the average failure rate during actual observations is as high as about 5% as shown in Table 2, which lists five random examples selected from LAMOST observation results taken from 2014/12 to 2015/05. We infer that this difference in loss rate may arise from some other reasons. For example, some targets positioned by the fibers which are labeled 'abnormal' will be missed in the observation. The label 'abnormal' means that these fibers have failed during several positioning processes. The stepper motors for the fiber positioning units may miss some steps during the LAMOST survey. Additionally, we do not exclude some operational mistakes.

Nevertheless, the number of lost objects caused by fiber unit collisions reaches as high as 50 in every plate during observations. This can negatively impact the efficiency of LAMOST to some extent. However, as many objects as possible should be observed since one of LAMOST's scientific goals is to study the structure and evolution of the Galaxy. It is worthwhile to retrieve these lost targets from



Fig.5 The collision frame of the hardware processing system. The labels '1', '2' and '3' are a signal generation part, collision handling part and control system, respectively.



Fig. 6 A schematic drawing showing three types of collision signals.

the input catalogs. Handling collisions between the fiber positioning units is very necessary. We design a hardware system to handle these situations during the observation stage, which will be described in the next section.

3 COLLISION HANDLING SYSTEM

3.1 The Structure of the Hardware System

The hardware structure for the collision handling system is designed based on two programs which were built by the method of voltage change inspection (Yan et al. 2007) and pulse contrast (Yan et al. 2008). It has been simulated successfully for one fiber positioning unit by the software package Proteus, which is introduced in our series paper (Liu & Wang 2014). The circuit structure of the hardware for handling a collision includes three parts as shown in Figure 5.

The first is the signal generation part which is designed for detecting collisions between the fiber positioning units and is labeled as '1' in Figure 5. In this part we choose the MSC-51 series single chip microcontroller as the signal controller. The second is the part that handles colli-

Table 1 The Number of Lost Objects

Ν	2500		3500		6000		8000		10000		14000	
	4.5 mm	6 mm	4.5 mm	6 mm								
$p_{_{S_x}}/n_{_{S_x}}$	0.0022	0.005	0.0022	0.0049	0.0011	0.0024	0.0005	0.0011	0.0002	0.0004	0.0	0.0
	27	61	26	58	13	29	6	13	2	5	0	0
$p_{S_{xy}}/n_{S_{xy}}$	0	0.0001	0.0001	0.0002	0.0001	0.0002	0.0	0.0	0.0	0.0	0.0	0.0
	0	6	8	14	12	24	0	0	0	0	0	0
$\Sigma(n_{S_x}, n_{S_{xy}})$	27	67	34	62	25	53	6	13	2	5	0	0

Notes: (1) N means the number of targets in the input catalog. 4.5 mm is the theoretical minimal radius and 6 mm is a more reasonable value in calculation of the collision probability. (2) p_{S_x} is the collision probability when only two targets are in the overlapped domain and n_{S_x} ($n_{s_x} = N \times p_{S_x}$) is the number of lost targets. $p_{S_{xy}}$ is the collision probability when only three targets are in the overlapped domain and $n_{s_{xy}}$ ($n_{s_{xy}} = N \times p_{S_xy}$) is the number of lost targets. (3) The probability of more than three targets being in the overlapping domain in LAMOST is close to zero, so we do not list them in this table. (4) $\Sigma(n_2, n_3)$ is the total number of lost targets by considering n_2 and n_3 .

Table 2 Examples of Survey Strategies from the LAMOST General Survey, where M Represents the Number ofTargets Allocated from a Given Catalog

Plate	Time	M	Observed Objects	Lost Objects	Failure Rate
GAC100N17B1	2014-12-26 23:17:30	3765	3599	166	4.4%
HD053443N053939V01	2015-01-28 19:30:00	3618	3522	96	2.6%
GAC094N39M1	2015-02-23 20:20:06	3736	3638	98	2.5%
HD103827N055449B02	2015-03-25 21:17:17	3677	3536	141	3.8%
HD145035N124702V01	2015-05-26 21:32:15	3492	3366	126	3.6%

Notes: This sample was selected from a survey taken from 2014/12 to 2015/05.

sions and is labeled as '2' in Figure 5, which is the fiber unit controller that detects a collision based on the returned signal. The last part, labeled as '3' in Figure 5, is the microcomputer control system. In this system, a method implemented in Visual Basic (VB) and an RS-232 serial interface (Zhao et al. 2006) are utilized during the communications.

3.2 Design of the Simulated Experiment

3.2.1 Detection of collision signal

This part is designed to detect collisions and send the result to part '2'. The detection of collisions is based on pulse superposition. To detect this superposition coming from different fiber units, we should theoretically assign different pulses to the 4000 fiber units. Because of the relative position of adjacent fiber units, the overlapping region includes at most three units as seen in Figure 6. Therefore, we assign three types of pulses (A, B, C), which have the same frequency but different phases, as the detection signals for the 4000 fiber positioning units. This design can assure that all adjacent fiber signals are different.

The frequency of stepper motors used by the fiber units is 510 Hz. To detect collisions in real time, we apply a 200 μ s delay by using the MCU to generate collision signals. When collisions occur, the collision signals have multiple pulses in the same period. We choose the single chip STC89C52 as the core unit of the pulse signal generator through a combination of the hardware circuit and software programming. Therefore the frequency and amplitude of the waveform can be adjusted in a certain range. In the design, firstly we set a 1 ms timer interrupt using timer1 of the STC89S52 chip as the time period for counting the collision pulses. Second, during this period we count the collision pulses using counter0 in the chip. Third, when a timer1 interrupt occurs, if the value of counter0 is 5, it indicates there is no collision. However, if the value is between 10 and 15, this signifies collisions between one or two adjacent fiber units could have occurred.

3.2.2 Signal processing

This part describes how to process detection signals. It includes the host controller and slave controllers. The host controller receives information from the MCU and conveys commands to the sub-controller (MCU). The main steps are detailed as follows.

When the subsystem based on MCU sends the collision results to the microcomputer through a serial bus, the main program in the microcomputer receives the results and directly determines the actual position of the fiber units. As a result, the microcomputer can immediately survey the fiber position units with only the data received from a sub-controller.

Figures 7 and 8 illustrate the procedure for serial data communication including serial data reception and transmission.

The sub-controllers implement two functions. One is to receive the collision results and transfer them to the microcomputer control system, and the other is to execute instructions from the microcomputer. STC89C52 MCU produced by company ATMEL (Liu et al. 2012) is used to control the positive inversion of the stepper motor. The collision results will be sent to the microcomputer by MSC.



Fig. 7 The main controller for the collision handling system of the LAMOST fiber positioning units. The major function is sending the command to the sub-controller and retrieving the status of units.

The MCU will control the rotation direction of stepper motors used in the units when the instructions arrive (Liu & Wang 2014).

3.2.3 Serial communication

Serial communication between the microcomputer and single chips plays a key role in executing the above functions. By using MSC control, the microcomputer communicating with many MCUs controls the fiber unit stepper motors and returns collision event information automatically. The whole hardware circuit consists of slave MCUs, which are considered as second level systems, and the microcomputer. The MCU serial communication at a TTL level remains between 0 V and 5 V, while the microcomputer serial communication represents the RS-232 standard. The most feasible solution to connect these two serial ports is just plugging a MAX-232 between them to act as the serial interface (Ege et al. 2013). Thus, the steps in rotation of the unit motor are calculated by the microcomputer according to the position of the objects and transmitted through the serial bus (Tian et al. 2007), which connects the microcomputer with the sub-controller. During the implementation, one or two standard serial ports (COM1 or COM2) facilitate communication through VB programming.

3.3 Result Analysis

These three modules operate through the functionality of the modules. When collisions occur between adjacent fiber positioning units during the observation, the hardware system is effective in handling this situation. The signal gen-



Fig.8 The sub-controller of the collision handling system for LAMOST fiber positioning units. The program includes receiving and feeding back information about control units from the main controller.

erator can be counted by the sub-controller without an AD converter, and it also has the advantages of small volume, low price, stable performance and complete functionality. The serial communication method has a simple connection, high reliability, low cost, etc. This simulated experiment considers seven close neighbor fiber units. When this system is put into use for 4000 fiber units, the sub-controller MCU should be exchanged with a field gate programable array (FPGA) which has high integration ability such that one chip of an FPGA can control more fiber units.

4 SUMMARY

In this work, we first analyze the probability of collision between fiber positioning units. To derive this probability, we assume that the allocation of the targets in the focal plane is uniform, so it follows a binomial distribution. Table 1 shows two boundaries defined by the radius of S_x , r = 4.5 mm and r = 6 mm. In fact, the most probable collision may happen at the radius 5 mm (between 4.5 mm and 6 mm) of S_x . If we choose the radius as 5 mm, the most probable number of collisions of the fiber units will be about 67 when the number of targets allocated in the focal surface is about 3500. It is worthwhile finding a way to handle these collisions between fiber units. We developed a new real-time hardware collision handling system for LAMOST fiber positioning units. It is a master-slave control system. In the design we use a microcomputer as our host controller which sends the position data and collision handling commands to the sub-controllers. A STC89C52 single-chip computer is used as a slave controller which receives commands from the host controller and accepts feedback in the form of data.

Through this system, the broken fiber units can be accurately identified and efficiently changed. In addition, it can improve the efficiency of LAMOST fiber units and the completeness of the survey. Because LAMOST has been operating for several years, some fiber units should be repaired or replaced at regular intervals. To a certain extent, the hardware system may also lengthen the service time of the fiber units. Because this is part of a complex system for handling 4000 fiber units, further research is required in the future.

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