Research on dynamic performance of star tracker

SUN Ting[1,2,3], XING Fei[1,2,3*], YOU Zheng[1,2,3]

(1. *Department of Precision Instrument*, *Tsinghua University*, *Beijing* 100084, *China*

2. *State Key Laboratory of Precision Measurement Technology and Instruments*, *Tsinghua University*, *Beijing* 100084, *China*

3. *Collaborative Innovation Center for Micro/Nano Fabrication*, *Device and System*, *Tsinghua University*, *Beijing* 100084, *China*

* *xingfei@mail.tsinghua.edu.cn*)

Abstract: This manuscript briefly summarizes the development trends and recent research focus of the star tracker. And the relevant technologies about dynamic performance of the star tracker are analyzed and discussed. These can provide reference for the star tracker and attitude measurement device researchers.

Key words: Star tracker; dynamic star image processing; restoration of star image; deep coupling

1 Introduction

With the development of space technology such as deep-space exploration, Earth observation and celestial navigation, the requirements for attitude measurement are definitely increasing. The star tracker is supposed to be greatly promising among different types of attitude measurement devices[1] for its high accuracy and drift-less characteristic.

When the star tracker works, after capturing a star image, the navigation star s_i can have an image on the star tracker sensor. After star extraction and star spot centroid determination, the directional vector under star tracker coordinate system w_i can be obtained. The vector v_i under inertial coordinate system can then be acquired with star identification and with the information in the star catalog.

The optimal attitude matrix A_q in the inertial space of the star tracker can be calculated by solving the relationship between vector w_i and v_i under the two coordinate systems with the QUEST algorithm[2].

1.1 Development of star tracker technology

The development of the star tracker has experienced more than half a century. The initial star tracker adopts photomultiplier as the detector, while it is an analog device and has limitations in accuracy and stability. Charge Coupled Devices and Charge Injection Devices bring great chance for the new generation star tracker[3-4]. The performance of the star tracker gets improved. Meanwhile, APS CMOS detector[5-6] gradually develops. Considering that APS CMOS detector has characteristic of high integration, the star tracker goes on the way of miniaturization. The two image detectors have been two major detectors employed to star tracker by now. The choices can be flexible in consideration of different space missions.

The main star tracker research organizations and products includeAstro series of Jena-Optronik GmbH in Germany[7-8], SED series and HYDRA of EADS Sodern company in France[9]; CT series, FSC series and HAST of Ball Aerospace & Technologies Corp. in the United States[10]; A-STR series of Selex Galileo Company in Italy[11-12]; ASC of Technical University of Denmark[13-15], and Surrey Satellite Technology Limited in England[16]. The pointing accuracy of the star tracker is generally around 3″-10″ (3σ), and may be superior to 1″(3σ). The data updating rate is generally around 1Hz-10Hz, and may be superior to 30Hz. The mass is generally around 1kg-6kg, and the power is around 5W-15W. CCD and APS CMOS detectors apply to different requirements. In the aspect of dynamic performance, the required angular velocity is nearly 0.5°/s with full performance, and may reach 2°/s with reduced performance.

1.2 Recent research focus of star tracker technology

The spacecraft develops continuously aiming for being more intelligent and miniature[17]. The researches of improving the characteristic of attitude measurement devices are demanding. The latest advances and hot issues mainly concentrate on the following aspects:

(1) High accuracy. There have been considerable researches about accuracy improvement technology. The studies include: star spot extraction algorithm[18-20], noise suppression method[21], calibration method [22-24], accuracy measurement method[25], Multiple field of view star tracker technology and so on. High accuracy is always one key index for the star tracker in the future development.

(2) Miniaturization. The increasing interest in micro ornano satellite spacecraft creates a market for a small, high accuracy star tracker. Sinclair Interplanetary, and Ryerson University have developed an autonomous star tracker ST-16 using on lager nanosatellites[26-27]. Several specifications of the ST-16 star tracker are exciting, such as the mass is around 90g, the cross-based accuracy is 7 arc-seconds in ground-based tests, and the rate tolerance can reach 2 deg/s[28].

(3) Dynamic performance. When the star tracker works, star extraction and star spot centroid determination are essential. In the dynamic case, smearing of the star spot will become inevitable during the exposure time, and the limited star energy will disperse into more pixels than static PSF, which decrease the signal to noise ratio (SNR) of the star spot. As a result, star extraction will become more difficult or even failed, and the star spot centroid will be inaccuracy. These may hinder the application of the star tracker in highly dynamic conditions.

There are several important approaches to improve the dynamic performance of the star tracker:

a) Improving from the star image. According to the feature of the dynamic star image, processing methods can be considered: establishment of dynamic degradation model of the star spot[29], smearing star image processing and restoration[30-31], smearing star spot centroid determination[32-33].

b) Improving from the hardware and configuration. Adopting a high performance image sensor, circuit design optimization, imaging pattern optimization[34], and exposure time optimization[35] are alternative choices.

c) Multi-sensor fusion. Additional transducers and sensors can be adopted to make data fusion with the star tracker. Collaboration between star tracker and gyroscope, collaboration between star tracker and Earth sensor, or similar combinations and data fusion have been studied to realize better performance and more functions such as wide dynamic range[36], gyroless guidance system[37-38], integrated guidance system[39-40] and celestial navigation[41-42].

2 Research advances of star tracker on dynamic performance

Tsinghua University has been studying on star tracker and relevant attitude determination devices for decades. In recent years, the authors are dedicated to star tracker technologies discussed in section 1.2. The research results involve star tracker calibration[43], single dynamic star image processing[44], dynamic star spot restoration[45], deep coupling of star tracker and MEMS-gyro data under uniform angular velocity and variable angular velocity[46]. The following is brief introductions of the principles and experiments.

Figure 1 shows the optical error propagation model of the star tracker. Through deducing, the deviation of the focal length Δf, the deviation of the optical axis Δs, the star point extraction error Δx and distortion value Δd are analyzed, and the expression of angle measurement error is obtained in Equation(1).

$$\xi_A = \arctan\left(\frac{\left(\frac{f + \Delta f + \Delta s \cdot \tan(\theta)}{\cos(\theta + \beta_{ri})} \cdot \sin(\beta_{ri}) + \frac{\Delta s}{\cos(\theta)} + \Delta x + \Delta d\right)}{f}\right) - \arctan\left(\frac{\Delta s}{f\cos(\theta)}\right) - \beta_{ri} \tag{1}$$

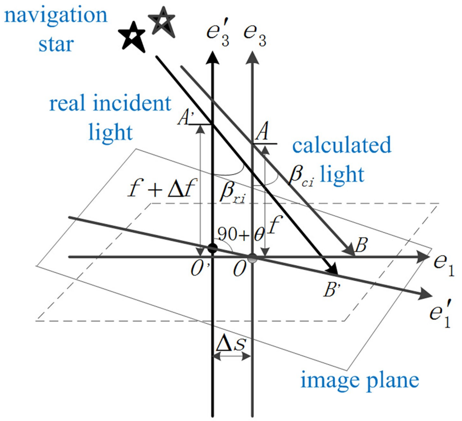

Fig. 1 Sketch of error propagation model of the star tracker[43]

There are two novel aspects in this calibration method. One is that the plate-glass in front of the lens is used as the reference of the principal point and other parameters calibration shown in Figure 2(a). Thus, it is convenient to unify the internal and external elements. The other aspect is that centrosymetric star points on the image sensor are used to distinguish the deviation brought by the radial distortion from the deviation brought by inclination of the image sensor (shown in Figure 2(b)). Calibration is the foundation of further research.

Then the dynamic performance of the star tracker is discussed. Through the star acquisition approach proposed in Reference [44], a combination of correlation filter and mathematical morphology algorithm is used to perform denoising, star point energy enhancement, background noise estimation and adaptive threshold setting. Thus, the reference window for extracting smearing star point information can be determined as shown in Figure 3. Partial image differentiation is utilized to obtain motion parameters. The reference window can be adjusted according to motion direction and extent, and the centroid determination can be finally performed.

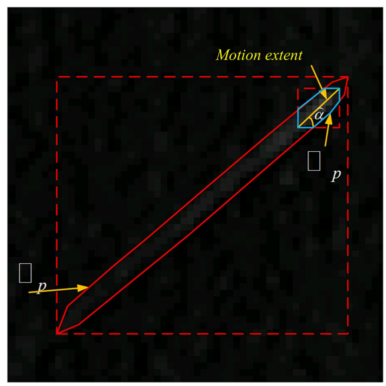

Fig. 3 The schematic of star extraction and centroid determination with reference window for one star region[44]

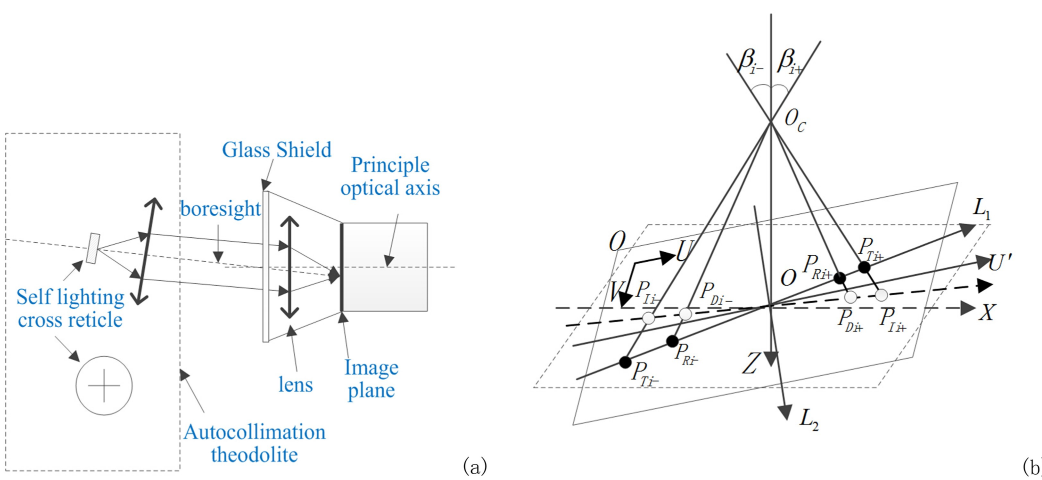

Fig. 2 Star tracker calibration device (a) and calibration schematic diagram (b)[43]

The following Figure 4 and Figure 5 display the differences between the results with and without proposed star acquisition method separately. Red numbers in the Figures represent extracted stars and green number represent identified stars. Figure 5 shows that more stars can be extracted and identified using the star extraction method. (b), (c), and (d) shows the gray values of one star point. The star point is difficult to observe in Figure 4 and is more obvious in Figure 5 as the energy of the star point is enhanced and the noise suppressed with the method.

Above star acquisition method mainly concerns using one star image without gyro information. The following method proposed in Reference [45-46] considers data fusion between star tracker and gyro to improve the dynamic performance of the star tracker. This data fusion method is not at the output attitude data level, but at the star image level as shown in Figure 6. The deep coupling method has several advances: first, the gyro angular velocity can provide useful information for the star image processing and star spot restoration under high dynamic conditions; second, the position of the star spot as well as MEMS-gyro drift can be optimally estimated to ensure high accuracy of the system. Figure 7 is the procedure of dynamic star image processing and restoration. Figure 8 is the crucial flow chart of the extend Kalman filter between the star tracker and gyro at the star image level.

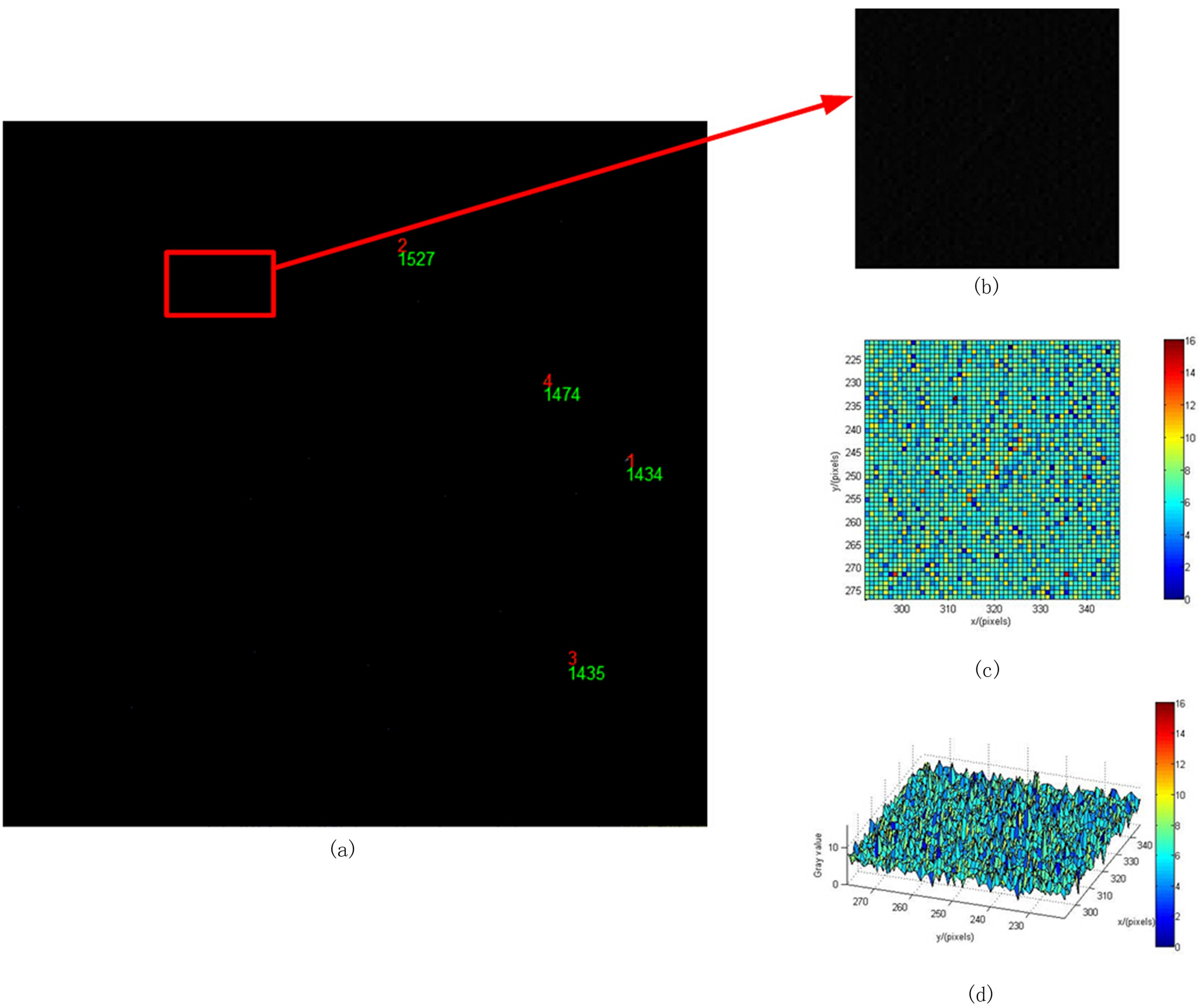

Fig. 4 Star extraction and recognition results without extra processing method, (b), (c), (d) are gray scale, colour scale and 3D plots of the same detailed view of one star point[44]

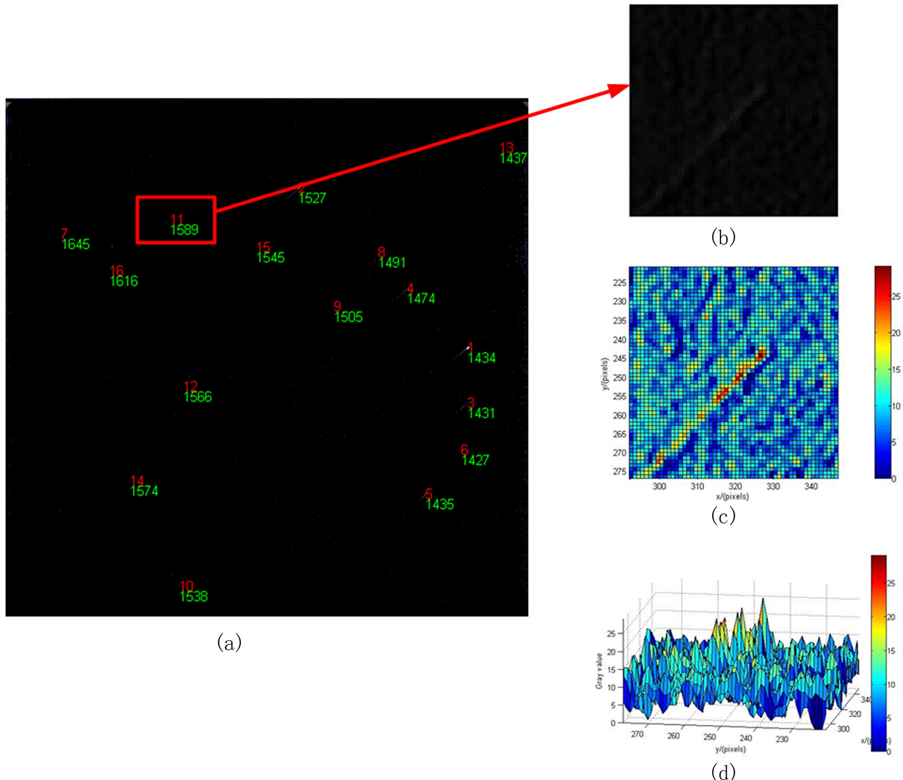

Fig. 5 Star extraction and recognition result with processing method in Reference[44], (b), (c), (d) are gray scale, colour scale and 3D plots of the same detailed view of one star point[44]

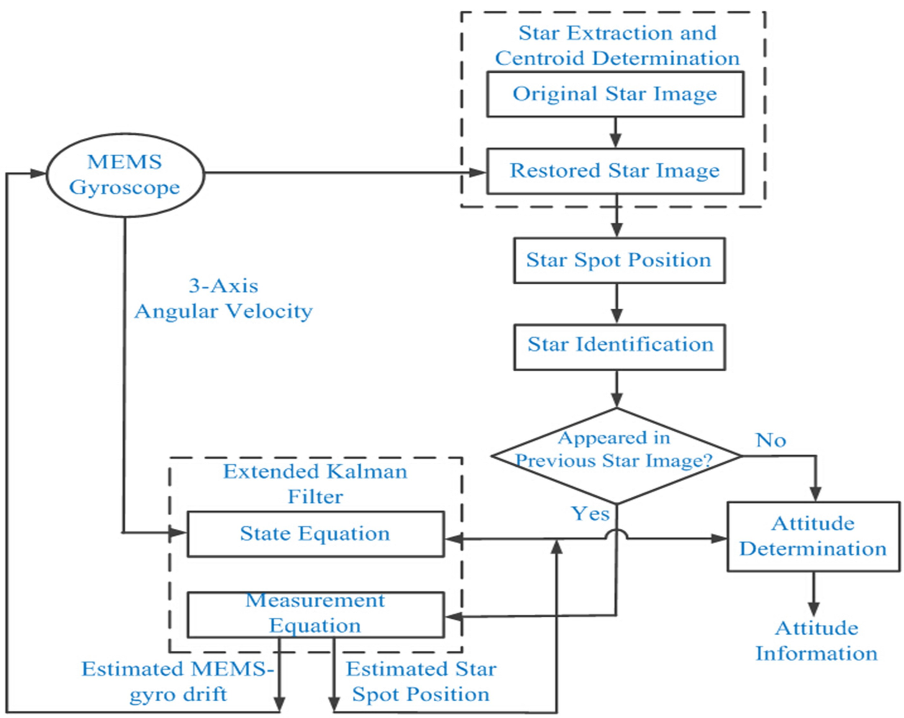

Fig. 6 Flow diagram of deep coupling of star tracker and MEMS-gyro data[46]

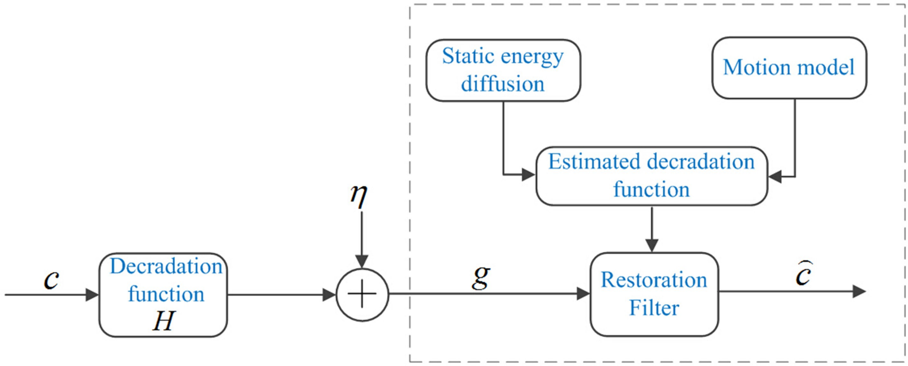

Fig. 7 Degradation and restoration process model[45]

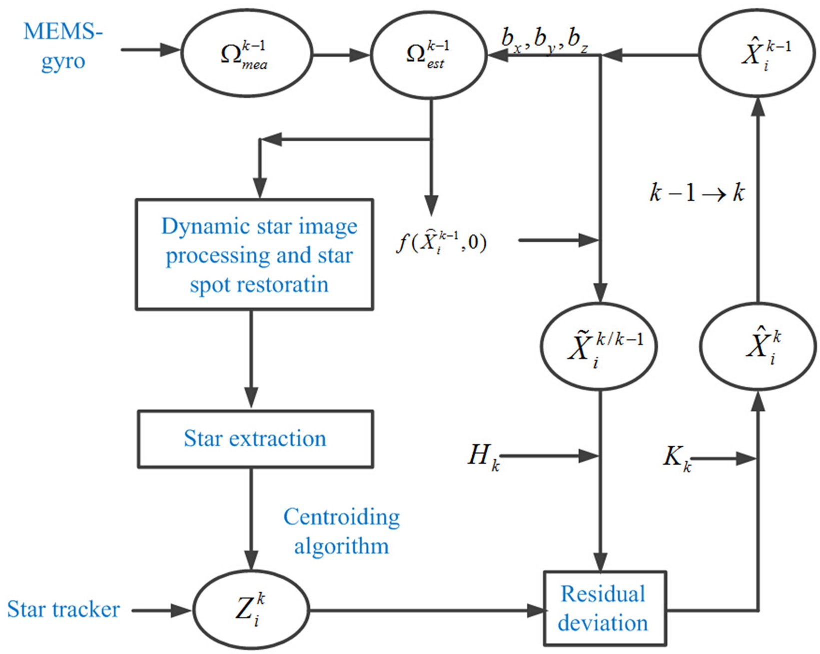

Fig. 8 Flow chart of the deep coupling of star tracker and MEMS-gyro data for determining the position of star spots and gyro drift[46]

The consequences have been demonstrated by simulation, experiments in laboratory, real night sky experiment and on-orbit star image. The following figures show some of the experiment environments.

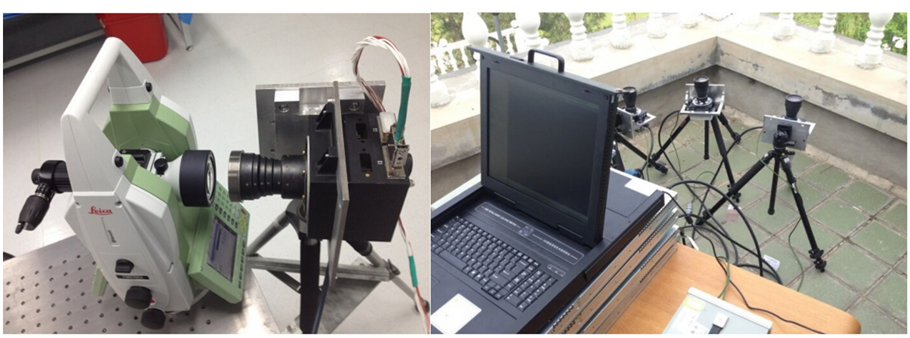

Fig. 9 Calibration experiment and real night sky experiment

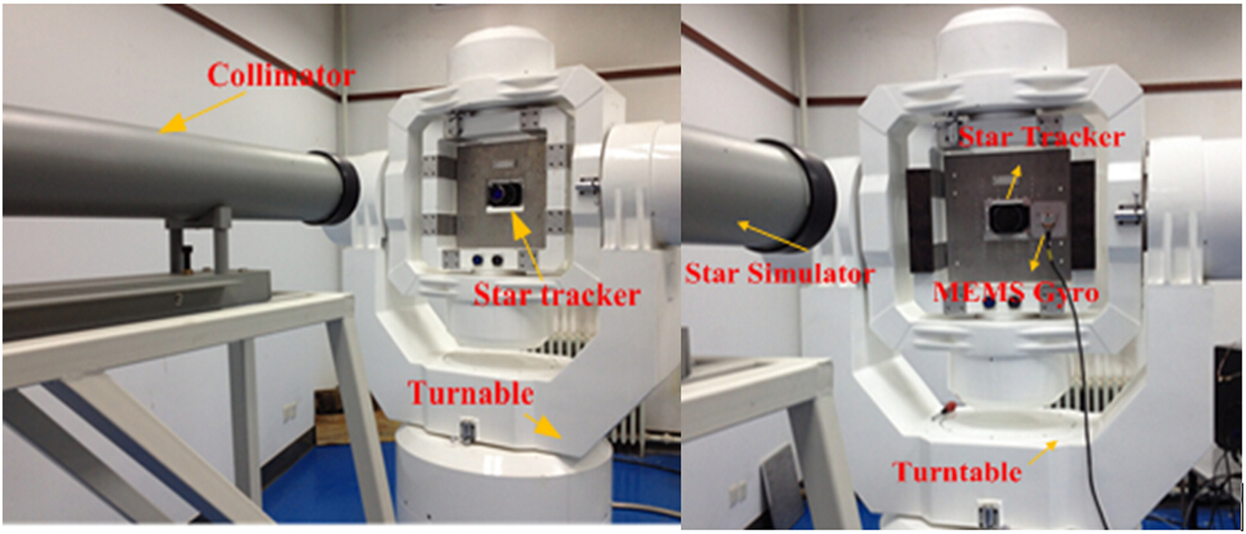

Fig. 10 Dynamic performance experiment

3 Conclusions

This manuscriptdiscusses development and recent research focus of the star tracker. One of the limitations of the star tracker: dynamic performance is particularly investigated. Review and analysis are conducted on degradation model, restoration of the star image, exposure time and imaging pattern optimization, and multi-sensor fusion. The future research trends in the dynamic performance of the star tracker are also analyzed.

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Authors' Biographies

SUN Ting, born in 1986, is currently a postdoctoral fellow in the Department of Precision Instrument, Tsinghua University, China. She obtained her Ph.D degree from Tsinghua University in 2014. Her major interests include high accuracy and high dynamic performance star tracker technology, etc.

Email: suntingthu@126.com

XING Fei, born in 1979, is currently an associate professor in Tsinghua University, China. He received his Bachelor degree from Tongji University in 2002 and Ph.D. degree from Tsinghua University in 2007. His current research

interests focus on advance optical attitude sensor for space, remote sensing and celestial navigation.
Email: xingfei@tsinghua.edu.cn

YOU Zheng, born in 1963, is an Academician of Chinese Academy of Engineering, and a Professor of Chang Jiang Scholar in Tsinghua University, China. He is also the Assistant President of Tsinghua University, the Dean of the School of Mechanical Engineering and the Chairman of the Department Precision Instrument. Respectively. His current research includes MNT technology, Micro/Nano satellite technology and their applications.
Email: yz-dpi@tsinghua.edu.cn