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Dual-beam laser autofocusing system based on liquid lens

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ABSTRACT

A dual-beam laser autofocusing system is designed in this paper. The autofocusing system is based on a liquid lens with less moving parts and fast response time, which makes the system simple, reliable, compact and fast. A novel scheme “Time-sharing focus, fast conversion” is innovatively proposed. The scheme effectively solves the problem that the guiding laser and the working laser cannot focus at the same target point because of the existence of chromatic aberration. This scheme not only makes both guiding laser and working laser achieve optimal focusing in guiding stage and working stage respectively, but also greatly reduces the system complexity and simplifies the focusing process as well as makes autofocusing time of the working laser reduce to about 10 ms. In the distance range of 1 m to 30 m, the autofocusing spot size is kept under 4.3 mm at 30 m and just 0.18 mm at 1 m. The spot size is much less influenced by the target distance compared with the collimated laser with a micro divergence angle for its self-adaptivity. The dual-beam laser autofocusing system based on liquid lens is fully automatic, compact and efficient. It is fully meet the need of dynamicity and adaptivity and it will play an important role in a number of long-range control applications.

1. Introduction

Dual-beam laser autofocusing system is widely used in long-range control, such as FMCW laser ranging [1,2], remote laser processing, laser marking, laser welding [3], velocity measurement, remote sensing, non-contact vibration measurement with laser [4] and so on. Dual-beam includes a guiding laser and a working laser. The guiding laser is visible and is used to find the target point accurately. The working laser is usually infrared laser and is used for laser processing, ranging or velocity measurement, etc. The two laser beams couple together. It is necessary that both lasers can focus automatically with the distance of the target point. On the one hand, the focused guiding laser is a requirement in accurate guiding, on the other hand, some applications have strict requirements on the spot size of the working laser. For example, the ranging error of FMCW laser ranging system is proportional to the spot size. The large spot will decrease the ranging accuracy. In laser processing, large spot will make the center energy cannot meet the processing requirement [5].

In the experimental stage, guiding laser is usually not used as the infrared laser can be seen by using an infrared viewing card and the focus process can be adjusted manually. However, from an implementation standpoint, the guiding laser is an essential part for the sake that the whole process needs to be fully automatic. Up to now, few investigations have been done on dual-beam laser autofocusing system.

There are two major obstacles must be overcome before a fully automated system can be realized: one is the choice of varifocal optical system, the other is the guiding laser and the working laser cannot focus at the same point with the influence of chromatic aberration.

Varifocal optical system can meet the requirements of autofocusing by changing optical parameters of optical components to adjust optical path [6]. A simple sketch of dual-beam laser autofocusing system is shown in Fig. 1. The coupled lasers pass through the varifocal system and focus at the target point automatically. Traditional varifocal optical system consists of several lenses whose position is continually adjustable. Focusing can be achieved via the external focus mechanism [7–10]. With rapid development, traditional varifocal optical system used to take up a wide application market. However, there are obvious disadvantages in this kind of system: Firstly, mechanical focus needs accurate control of position in lens' movement. So before moving, it is necessary to calculate the precise movement path, and each lens' movement should be synchronous. These stringent requirements make the automatic focusing system complex, processing difficult, and expensive. Secondly, the lens' moving will make the components easy to wear. As a result, the life of the system is short. Thirdly, the change of the focal length is based on the change of the mechanical length. This will make the system size too large to meet the requirement of miniaturization [11–13].

Besides the existing defect in traditional varifocal system, there is another design challenge in designing dual-beam laser autofocusing system. According to convex lens imaging principle, when keeping

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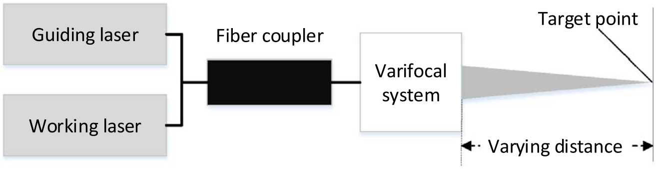

Fig. 1. A simple sketch of dual-beam laser autofocusing system.

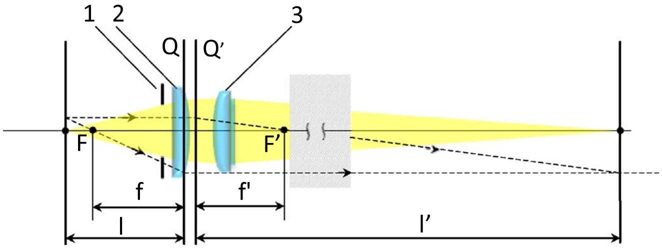

Fig. 2. ZEMAX simulation model, where 1 is the stop, 2 is the offset lens and 3 is the liquid lens, Q and Q' are the object principal plane and image principal plane, F and F' are object focal point and image focal point, f and f' are object focal length and image focal length, l and l' are object distance and image distance.

Table 1
ZEMAX simulation results with different offset lenses.

Focal length of offset lens	Object distance	Numerical aperture		Allowed largest divergence angle	
		658 nm	1550 nm	658 nm	1550 nm
No offset lens	198 mm	0.02424996	0.0242431	1.3896°	1.3892°
	133 mm	0.03498091	0.03497036	2.0047°	2.0041°
	82 mm	0.05357332	0.05355553	3.071°	3.07°
100 mm	60 mm	0.0739341	0.07375284	4.24°	4.2296°
	41 mm	0.09857463	0.09833343	5.6571°	5.6432°
50 mm	33 mm	0.1236059	0.1230299	7.1003°	7.067°
	26 mm	0.1435772	0.1429199	8.2549°	8.2168°
40 mm	27 mm	0.1461826	0.1453255	8.4058°	8.3561°
	22 mm	0.164424	0.1634789	9.4638°	9.4089°
30 mm	19 mm	0.1910531	0.1895009	11.014°	10.924°
	18 mm	0.1961337	0.194551	11.311°	11.218°
	17 mm	0.2014876	0.1998741	11.624°	11.53°
25 mm	15 mm	0.2281649	0.2257527	13.189°	13.047°
	14 mm	0.2345933	0.2321417	13.568°	13.423°
20 mm	11 mm	0.2839441	0.2834552	16.496°	16.467°
15 mm	7 mm	0.3474966	0.3469841	20.334°	20.303°

object distance unchanged, adjusting the focal length of the varifocal system to make it gradually approach to the value of object distance but always below it, the image position of the light beam will go to infinity [14]. Unfortunately, there is usually a big difference between the frequency of the guiding laser and the working laser, so chromatic aberration cannot be ignored and it cannot be corrected by conventional method like the using of achromatic lens. With the target distance increasing, if just maintain the guiding laser in autofocusing state, the working laser will go from convergence to divergence, it never converge to a point but form a large spot, which will severely disrupt the system performance. In other words, the guiding laser and working laser cannot focus at one target point simultaneously because the existence of chromatic aberration.

To solve the above-mentioned problem, this paper designs a dual-beam laser autofocusing system based on the newest technology—liquid lens. In addition, a novel scheme "Time-sharing focusing, fast conversion" is proposed to eliminate the influence of chromatic aberration. The wavelengths of the guiding laser and working laser used in the system are 658 nm and 1550 nm respectively, which is widely used in FMCW laser ranging system. For other systems, the wavelengths of guiding laser and working laser may be different. But the autofocusing system also applies by just changing some constant parameter values of the system. This system can achieve the effect that both guiding laser and working laser focus automatically at the target point within the distance range spanning from 1 m to 30 m. This system possesses the practical value for its advantages of small size, short focusing time, low complexity and free from being affected by chromatic aberration.

2. Design of dual-beam laser autofocusing system

2.1. Choice of varifocal system

Traditionally, axial focusing is achieved using complex mechanics by moving either the target or the optical components. This can be expensive, slow and unreliable [15,16]. To remedy such insufficient, electrically focus tunable lens is used. Electrically focus tunable lens gives a possibility to design optical systems, which have no analogy in classical systems [17].

In this paper, we choose Optotune's electrically focus tunable liquid lens instead of traditional mechanical focusing system. The liquid lens technology is an emerging technology. It is a shape-changing lens with variable focal length [18–20]. It consists of a cavity membrane, an elastic polymer membrane that filled with an optical fluid. There is an electromagnetic actuator that used to exert pressure on the cavity membrane. The curvature of this shape changing polymer lens is adjusted by the pressure [21]. The optical power of the liquid lens is proportional to the pressure in the fluid, or the current flowing through the electromagnetic actuator. The focal length can be turned to a desired value within milliseconds [22,23].

The focal tuning range of the liquid lens used in this paper is +80 to +200 mm, but the range can be changed because the protective cover glass can be replaced by an offset lens. This allows shifting the focal length range to any desired value. The liquid lens has less moving parts and fast response time, which makes the overall system more reliable, compact and less expensive [24].

2.2. System simulation and parameter optimization

The focal tuning range of the liquid lens we chosen is +80 to +200 mm. According to the principle of autofocus, the distance between fiber and liquid lens should be large than 80 mm. The divergence angle of 658 nm laser and 1550 nm laser are about 6. 5° and 10.7° respectively. When the distance between fiber and liquid lens is long, equal part of laser beam cannot enter into the liquid lens, which will cause large energy loss and make the size of the system large. Therefore, an offset lens is needed to adjust the focal tuning range.

The apply range of the system is 1–30 m. By simulation with ZEMAX software, focal length of the offset lens and the distance between fiber and offset lens were designed and optimized. The simulation model is illustrated in Fig. 2.

The simulation results including the focal length of the offset lens, object distance, numerical aperture and the allowed largest divergence angle are shown in Table 1. In column "Object distance", the first number is the maximum allowed object distance and the last number is the minimum allowed object distance corresponding to each offset lens. (Simulations were carried out under the different conditions of 658 nm and 1550 nm respectively).

From Table 1 it can be seen that the numerical aperture as well as the allowed largest divergence angle of the beams increased with decreasing of the focal length of offset lens. When the focal length of the offset lens is 30 mm and smaller, the allowed largest divergence angle makes it possible that both 658 nm laser and 1550 nm laser can passing through the liquid lens with no energy loss. Simultaneously,