A Low-Cost Laser Barrier Based Vectorial Velocity Measurement System

S. Lindner, R. Weigel, and A. Koelpin
Institute for Electronics Engineering, University of Erlangen-Nuremberg
91058 Erlangen, Germany
Email: Stefan.Lindner@fau.de Phone: +49 9131/85-28847

***Abstract*—This paper describes a low-cost measurement system based on two crossed laser barriers to measure the angle, the position as well as the velocity of an object with known shape, which is passing the measurement system. Due to the simple system setup this leads to a low-cost vectorial speed measurement system, which is capable of high speed measurements. Furthermore, as a demonstrator, a table soccer ball speed measurement system will be presented, which shows the feasibility of the proposed system.**

***Index Terms*—angle of arrival, velocity measurement, laser barrier,crossed laser, table soccer**

I. Introduction

Speed measurement is a frequent task in a lot of disciplines, e.g., traffic surveillance, industrial sensors, military sensors, and in a variety of sport scenarios.

This paper mainly focuses the last one, and to be more precise, the detection of round objects, i.e., in the most cases balls. The knowledge of the speed of the ball can be very interesting for competitions, as well as for training purposes.

The detection of such small, fast moving objects can be done, e.g., with cameras, radar sensors or laser barrier setups. The camera based setup is quite versatile, because it can handle complex target shapes and it can track several objects and complex trajectories [1]. Unfortunately, the hardware is expensive, and the following data processing complicated. A further drawback is that the maximum detectable velocities of the targets are limited due to the frame rate of the camera. Using a Doppler radar sensor is another easy and nowadays low-cost approach for such a task. Nevertheless, the measured velocity depends on the angle of arrival, which can be suppressed at higher costs using a dual receiver architecture with several antennas to detect the angle of arrival and correct the result. Anyway, it comes with the drawback, that the target has to have a significant radar cross section, e.g., a metallic surface.

This paper proposes a laser based system which is capable of detection of small, round, and fast moving non-transparent objects. After a short introduction of laser barrier based speed measurement, the system will be explained by the help of a demonstrator setup for a table soccer ball speed measurement system and an appropriate calibration and reference structure. The result from this setup will show the system's high accuracy.

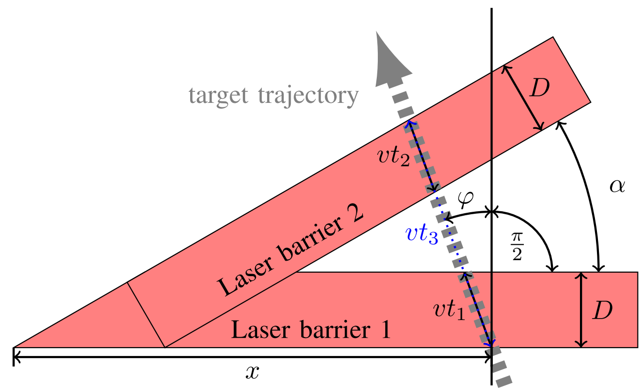

Fig. 1. Geometrical properties of the proposed system

II. Laser based Velocity Measurement

Using a light barrier is a low-cost and precise solution to determine an accurate value of the velocity of a moving target [2]. In the following, the commonly used systems will be explained:

A. Single Laser Solution

The simplest solution would be to use a single laser placed perpendicular to the transit path of the object and measure the transition time of the target. Then, the velocity can easily be calculated with knowledge of the geometrical length in the direction of transition, i.e., in our case the diameter. Nevertheless, this approach leads to errors, if the target did not pass at an angle of exactly $\frac{\pi}{2}$.

B. Dual Laser Solution

The influence of this angle of transit can suppressed using two parallel lasers and measuring the time, when the target is between the two barriers. With knowledge of the distance between the barriers and the size of the target the velocity can be calculated. Nevertheless, using this principle, the angle can not be detected, only its influence will be removed.

C. Dual crossed Laser Solution

The proposed system uses also two laser barriers, with the difference to B, that the laser barriers are not in parallel, but crossed with an angle α. Therefore, the transition time of the two barriers are not the same and with this additional degree

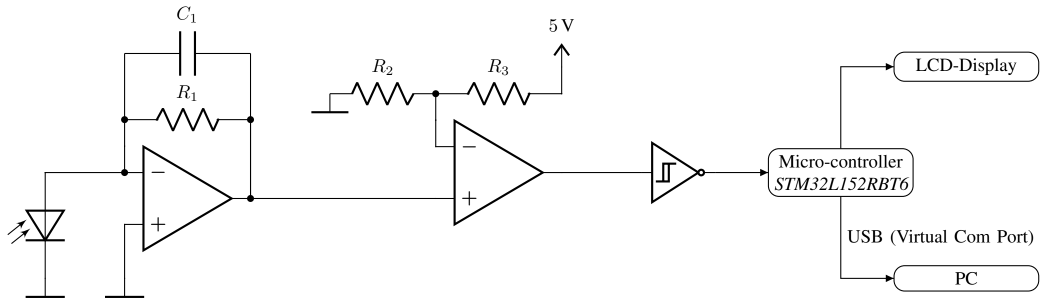

Fig. 2. Read out circuitry for photo diode

of freedom, the angle of arrival as well as the position of entrance at the first light barrier can be determined.

The geometrical properties of this system are depicted in Figure 1. The drawn width of the light barriers D corresponds to the diameter of the target passing the system and the times of interrogation, respectively. Furthermore, it is clearly recognizable, that the angle α has to be chosen carefully. For too small angles, the times t_1, t_2 could not be measured anymore. On the other hand, a high value of the angle leads to a long dwell time of the DUT within the sensor, therefore the velocity is not constant, which leads to measurement errors.

III. Mathematical Calculation

After the measurement of the two interruption times t_1, t_2 of the lasers and the whole retention time between the barriers t_3, the three unknown values of interest can be calculated. Due to dependence of each other, at first the angle of arrival, then the velocity and at the end the position of the transmission has to be calculated.

A. Angle

The angle of arrival φ, which is actually the deviation from an angle of $\frac{\pi}{2}$, is calculated by comparing the transition times t_1 and t_2 with knowledge of the angle between the light barriers α.

$$\varphi = \arctan\left(\frac{\cos(\alpha) - \frac{t_1}{t_2}}{\sin(\alpha)}\right) \tag{1}$$

B. Velocity

The velocity v of the object is calculated using the transition time of the first laser barrier compensated by a correction factor due to the incident angle φ.

$$v = \frac{D}{t_1 \cos(\varphi)} \tag{2}$$

C. Position

Using the last measured quantity t_3, also the position of impact x, which is the distance from the crossing point of the light barriers to the position of entrance of the target, can be evaluated depending on the previous results.

$$x = \frac{v t_3 \cos(\alpha + \varphi)}{\sin(\alpha)} \tag{3}$$

IV. Demonstrator Hardware Description

For demonstration purpose, one half of a table soccer was constructed having the proposed system build inside the goal. Additionally, a calibration and reference hardware was constructed to measure the accuracy of the measurement system, consisting of a well-defined inclined plane of different heights comprising only minimal friction to the ball.

A. Laser barriers

For the demonstrator two crossed laser diodes at a wavelength of 850 nm with included lenses were used. To ensure the detection in the case of flying balls, the laser beams were redirected by two mirrors at both edges to implement a laser fence, which is sketched in Fig. 3.

B. Readout Circuitry

Fig.2 shows the readout circuitry of the laser barriers. The laser's light is detected at the opposite side using a photo detector with a maximum sensitivity for the used wavelength. The resulting photo current is translated to a corresponding voltage by the first operational amplifier, which is used as a trans-impedance amplifier. The gain of this translation can be adjusted using the resistor R_1. The capacitor C_1 ensures the stability of the circuit for high gain values. After the voltage conversion a comparator, built by the second operational amplifier, sets the threshold level for the detection of an object within the laser barrier. This threshold level can be adjusted by the resistors R_2 and R_3, respectively. A following Schmitt-trigger ensures the debouncing of the signal, before it is detected at an external-interrupt capable pin of the micro-controller.

The readout circuitry is connected to a STM32L-Discovery Kit comprising a STM32L152 micro-controller, which mea-

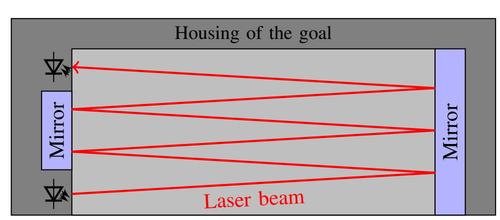

Fig. 3. Laser fence to enhance detection range using mirrors

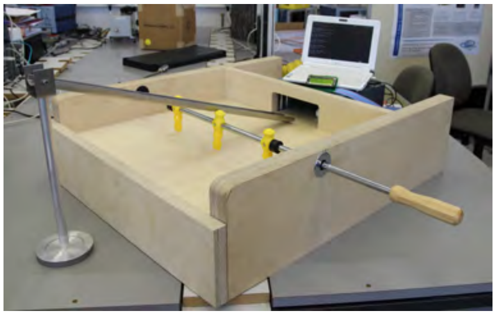

Fig. 4. Demonstrator setup with well-defined inclined plane for accuracy measurements

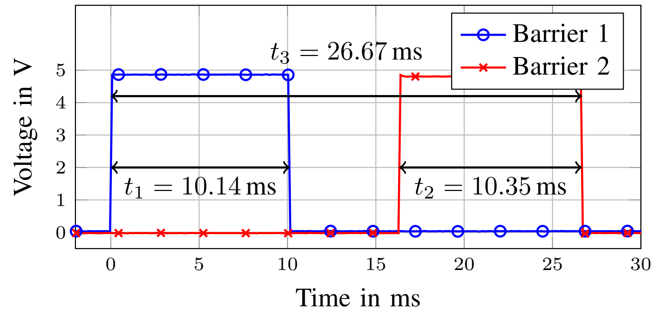

Fig. 5. Interruption event of both laser barriers measured at the oscilloscope

sures the interruption time using a hardware timer with a resolution of 30 ns and calculates the measurement results. The values can be observed at an integrated LCD display or read out via a USB virtual com port from a host PC.

C. Calibration and Velocity Reference

For the calibration of the system, i.e., the correct estimation of the angle α, an inclined plane was used with different heights to simulate different velocities. The setup for a calibration run is shown in Fig. 4.

The calibration is based on the equality of energy at the transformation from potential energy to translational energy and rotational energy, respectively.

$$W_{pot} = mgh \tag{4}$$

$$W_{trans} = \frac{1}{2}mv^2 \tag{5}$$

$$W_{rot} = \frac{1}{2}J\omega^2 = \frac{1}{2}J\frac{v^2}{r^2} \tag{6}$$

The rotational energy depends on the moment of inertia of the rotating object. Here, the soccer ball can be assumed as an ideal sphere, therefore, the moment of inertia is:

$$J_{spere} = \frac{2}{5}mr^2. \tag{7}$$

Solving the equation, without consideration of any friction between the ball and the inclined plane, leads to the velocity v of the rolling soccer ball at the end of the plane.

$$W_{pot} = W_{kin} = W_{trans} + W_{rot} \tag{8}$$

$$mgh = \frac{1}{2}mv^2 + \frac{1}{2}(\frac{2}{5}mr^2)\frac{v^2}{r^2} \tag{9}$$

$$mgh = \frac{1}{2}mv^2 + (\frac{1}{5}m)v^2 \tag{10}$$

$$v = \sqrt{\frac{10}{7}gh} \tag{11}$$

V. Measurement Results

Fig. 5 shows a measurement taken from an oscilloscope for a passing ball. The two interruptions of both laser barriers are clearly observable and leading to the marked time measurements t_1, t_2, and t_3, respectively.

To test the system with different speeds, and to get an idea of the system accuracy, different inclined planes with differing heights were used. The summarized results from those measurements can be found at Table I. For the measurement three heights were used and for the middle height three angle of arrival were tested. As pointed out by the measured values in the table, the mean measurement error is in all cases below $1\frac{\text{km}}{\text{h}}$ and the standard deviation is below $0.3\frac{\text{km}}{\text{h}}$, respectively.

TABLE I
Results of reference measurements with inclined plane

velocity	$5.1\frac{\text{km}}{\text{h}}$	$7.4\frac{\text{km}}{\text{h}}$	$7.4\frac{\text{km}}{\text{h}}$	$7.4\frac{\text{km}}{\text{h}}$	8.5 kmh
angle	$\approx 0°$	$\approx 0°$	$\approx -30°$	$\approx +30°$	$\approx 0°$
$\overline{v_{err}}$	$0.07\frac{\text{km}}{\text{h}}$	$-0.52\frac{\text{km}}{\text{h}}$	$-0.59\frac{\text{km}}{\text{h}}$	$-0.90\frac{\text{km}}{\text{h}}$	$-0.03\frac{\text{km}}{\text{h}}$
std(v_{err})	$0.077\frac{\text{km}}{\text{h}}$	$0.16\frac{\text{km}}{\text{h}}$	$0.30\frac{\text{km}}{\text{h}}$	$0.11\frac{\text{km}}{\text{h}}$	$0.11\frac{\text{km}}{\text{h}}$
$\overline{\varphi}_{meas}$	0.6°	5.5°	31.5°	-29.9°	-3.9°
std(φ_{meas})	2.0°	1.8°	2.7°	3.9°	3.1°

The residual errors can be traced back to the fact that the measurements were performed with different balls to get more practical results, nevertheless, due to the dependency of the velocity to the ball diameter, this also raises the resulting error. Furthermore, the friction of the ball is not considered at all, leading to an additional error. Especially, if the ball speed changes between the two laser barrier.

VI. Conclusion

A simple laser based velocity measurement system has been proposed, which is capable of high speed measurements of table soccer balls at every angle and position. Beside the information of the accurate velocity, also the position and relative angle of impact can be measured to maximize the training efficiency for professional players. It should be noted that this concept can easily be extended by a second system measuring the vertical component of the moving target to implement a system, which comprises the measurement of 3D trajectories.

References

[1] C. Theobalt, I. Albrecht, J. Haber, M. Magnor, and H.-P. Seidel, "Pitching a baseball: Tracking high-speed motion with multi-exposure images," *ACM Trans. Graph.*, vol. 23, no. 3, pp. 540–547, Aug. 2004.

[2] J. Liu and L. Yu, "Laser-based apparatus for measuring projectile velocity," in *Electronic Measurement Instruments, 2009. ICEMI '09. 9th International Conference on*, Aug 2009, pp. 2–595–2–598.