Experimental validations of simulated scan patterns of rotational Risley prisms

Dîmb, Alexandru-Lucian, Duma, Virgil-Florin
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Alexandru-Lucian Dimb¹b, Virgil-Florin Duma²a,¹

¹Doctoral School, Polytechnic University of Timisoara, 1 Mihai Viteazu Ave., 300222 Timisoara, Romania
²3OM Optomechatronics Group, Aurel Vlaicu University of Arad, 77 Revolutiei Ave., 310130 Arad, Romania

ABSTRACT

Laser scanners with Risley prisms have the potential to perform a faster scanning in comparison to other two-dimensional (2D) laser scanners, for example galvanometer-based. However, in contrast to the (constant speed) raster scanning produced by the latter, scan patterns of Risley prisms are highly non-linear, have intersection points, and are performed with variable speeds. The aim of this study is to build upon the novel, graphical method we have, to our knowledge, introduced for the study of these scan patterns. In contrast to complex analytical methods and to approximate ones, this graphical method is easy-to-apply and it provides exact scan patterns, respectively. In this study examples of experimental results are obtained to validate simulation results obtained using simple prisms equations and a commercially-available mechanical design program, CATIA V5 (Dassault Systèmes, Paris, France). Several characteristics of the laser scanner with a pair of rotational wedges are considered, with a focus on one of Marshall’s parameters, i.e. the ratio \( M \) of the rotational speeds of the prisms. An experimental validation is demonstrated for all characteristic graphs of the scan patterns for two pairs of values, \( M \) equals 2 or -2, as well as 8 and -8. The contrast between positive and negative values of \( M \), as well as between lower and higher absolute values can be thus observed. As this is but a step in this study, directions of current work are also pointed out.

Keywords: laser scanners, Risley prisms, rotational wedges, scan patterns, geometrical optics, modeling, multi-parametric analysis.

1. INTRODUCTION

Scanning systems with Risley prisms have in their most common configuration a pair of optical wedges [1]. These prisms usually perform rotations [2-9], but they also can have oscillatory [10] or translational movements [11]. Scanners with Risley prism are utilized in numerous applications, including laser scanning and pointing [1-10], interferometry [12-13], polarimetry [14], holography [15], interferometry [16], metrology [17], and confocal microscopy [18]. The main advantage of Risley prisms-based laser scanners in comparison to other types of scanning systems, notably galvanometer-based (GS) or Micro-Electro-Mechanical Systems (MEMS) with oscillatory mirrors [19,20], is the faster 2D scanning achieved in a more compact structure. Their disadvantages are related to the high non-linearity of the produced scan-patterns, which means a non-constant scanning speed along these trajectories, and eventually to their unsatisfactory fill factor (FF) for applications in imaging. From all these points of view the competitor of Risley prisms scanning (with pretty much the same pluses and minuses) is Lissajoux scanning, performed with a pair of orthogonal GSs or with MEMS [21]. With regard to these two scanning modalities, Risley prisms have the supplemental advantage of allowing for the miniaturization of the scanning system, making it appropriate for endoscopy, for example.

Rather complex analytical methods have been developed [5-7], as well as approximate ones [3], to study scan patterns of Risley prisms. In contrast to both these categories, we have proposed [22] and developed in detail [23], for the first time to our knowledge, a graphical method that is easy-to-apply and provides exact scan patterns, respectively. This method only utilizes the simplest prisms equations to simulate the light bundles that pass through the two prisms with a commercially available mechanical design program, CATIA V5 (Dassault Systèmes, Paris, France).

¹ Email: duma.virgil@osamember.org; phone: +40-751-511451; sites: http://3om-group-optomechatronics.ro/; https://www.researchgate.net/lab/3OM-Optomechatronics-Group-Virgil-Florin-Duma
The aim of this study is to compare exact scan patterns of a pair of rotational Risley prisms obtained using graphical method simulations and using experimental results obtained with the simplest possible experimental setup, consisting only of commercially available components, and with manual rotational stages. The aim is thus to perform an experimental validation of simulations obtained with the graphic method, considering several examples.

In the remaining of this paper, Section 2 presents the experimental setup and the utilized parameters of the laser scanner: $M$ ratio of the angular speeds, $k$ ratio of the prism angles, $e$ axial dimension of the device on the optical axis, $L$ distance from the final diopter of the second prism of the scanner to the screen/scanned plane, $n$ refractive index of both prisms. Section 3 presents a comparison between simulated and experimental scan patterns, as well as the evolution of their $x$ and $y$ coordinates, considering both methods. Conclusions are drawn in Section 4, and directions of future work are briefly pointed out.

2. EXPERIMENTAL SETUP OF A PAIR OF ROTATIONAL RISLEY PRISMS

A commercially-available mechanical design program, CATIA V5 has been utilized to obtain exact scan patterns of a pair of rotational Risley prisms, as presented in Fig. 1(a). The graphical method developed has been described in detail in [22], and further continued in [23]. Two light bundles thus obtained are presented in Fig. 2, for two values of Marshall’s $M$ parameter, 8 (in purple) and -8 (in red), to show the way scan patterns are drawn, at a constant distance from the scanner.

The experimental setup has been made with Thorlabs components, for this $ba$-$ab$ configuration (where ‘$a$’ means a prism diopter perpendicular on the optical axis (O.A.), while ‘$b$’ means a diopter tilted with regard to the O.A.) - Fig. 1(b). This experimental setup used the following parameters: $e = 25$ mm – distance between the ‘$a$’ dioptries of the scanner; $L = 1000$ mm – distance from the ‘$a$’ diopter to the screen/scanned plane; $n = 1.517$ – refractive index of both (identical) prisms. It must be specified that the setup is a manual one, i.e. the rotational stages are moved manually according to the considered Marshall’s parameter $M$ [3], which in this case is no longer achieved as the ratio of the rotational speeds of the prisms, but of their rotational angles for each incremental movement.

![Figure 1. (a) Laser scanner with rotational Risley prisms: modeling with a three-dimensional (3D) mechanical design program, CATIA V5R20; (b) Experimental setup with (Thorlabs, Newton, NJ, USA) components for the study of the scan patterns of a pair of rotational Risley prisms with motorized prism mounts. Components: (1) AC-DC power supply; (2) He-Ne laser; (3) kinematic V-groove mount; (4) wedge prisms; (5) wedge prism mounts; (6) high-precision rotation mount for Ø1"; (7) post and (8) post holder; (9), (10) translation stages; (11) aluminum breadboard.](image)

3. RESULTS AND DISCUSSION

A comparison is made in this study between scan patterns obtained with the graphical method by using CATIA V5 and those obtained experimentally. As two identical prisms have been considered, each with the maximum deviation angle of 2°, the other parameter introduced by Marshall (i.e. the ratio of the deviation angles of the prisms in paraxial) is $k = 1$. Four values of Marshall’s parameter $M$ have been considered in this study, as examples, i.e. ±2 and ±8.
The results of the performed simulations are presented in Figs. 3(a) to 6(a), with the experimental scan patterns superposed on the same graphs. The cartesian coordinates $x$ and $y$ have been also easily extracted from these scan pattern and they are presented in Figs. 3 to 6(b).

The contrast between the cases when positive and negative values of $M$ are considered (therefore when the prisms rotate in the same or in opposite directions, respectively) can be observed. One can also observe the differences between lower and higher absolute values of $M$, i.e. for $|M|=2$ and $|M|=8$.

One can also verify the equation of the number of loops [3], $\mu=|M|-1$, as well as [23], $\mu(M<0) = \mu(M>0) + 2$.

Several conclusions can be drawn from the contrast between simulations and experimental results:

(i) there is a difference between the two scan patterns, due to alignment errors and parameter evaluation when installing the experimental setup;
(ii) the shape of the scan patterns is preserved, for both the graphical and the experimental results, therefore a validation of the graphical method has been obtained;
(iii) the graphs of the $x$ and $y$ coordinates of the two scan patterns also have the same shape, almost overlapping.
Figure 3. Graphical scan patterns (blue line) and experimental ones (purple line) obtained for a pair of rotational Risley prisms, in the case of \( M=2 \) (and \( k=1 \)): (a) scan pattern in a plane perpendicular on the O.A.; (b) coordinates \( x \) and \( y \) of the laser spot in the scanned plane for each method.
Figure 4. Graphical scan patterns (blue line) and experimental ones (purple line) obtained for a pair of rotational Risley prisms, in the case of $M=2$ and $k=1$: (a) scan pattern in a plane perpendicular on the O.A.; (b) coordinates $x$ and $y$ of the laser spot in the scanned plane for each method.

Figure 5. Graphical scan patterns (blue line) and experimental ones (purple line) obtained for a pair of rotational Risley prisms, in the case of $M=8$ and $k=1$: (a) scan pattern in a plane perpendicular on the O.A.; (b) coordinates $x$ and $y$ of the laser spot in the scanned plane for each method.
Figure 6. Graphical scan patterns (blue line) and experimental ones (purple line) obtained for a pair of rotational Risley prisms, in the case of $M=-8$ (and $k=1$): (a) scan pattern in a plane perpendicular on the O.A.; (b) coordinates $x$ and $y$ of the laser spot in the scanned plane for each method.

4. CONCLUSIONS

This study validates experimentally the graphical method we have developed to obtain scan patterns of a pair of rotational Risley prisms – in all the four considered examples, for different values of the ratio of the rotational speeds of the prisms. Future work includes a comparative analysis (based on both simulations and experiments) of scan patterns obtained for different values of the other parameters of the scanner, including the $k$ parameter, as well as the characteristic distances $e$ and $L$ (as performed previously in [23]). A range of applications of Risley prisms are also envisaged, especially for scanning in biomedical imaging [25,26], as an alternative to the common raster scanning, but also to Lissajoux [21] and spiral scanning [27].

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