

surfaces and a smooth optical flat. As expected, the results reveal that the new areal spline filter not only possesses an isotropic transmission characteristic, but also inherits the ability to avoid end effects from the profile spline filtering algorithm.

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6. References

- [1] W. Zeng, X. Jiang, and P. J. Scott. Fast algorithm of the robust Gaussian regression filter for areal surface analysis. *Measurement Science and Technology* 2010; 21(5):1-9. <http://dx.doi.org/10.1088/0957-0233/21/5/055108>
- [2] X. Jiang and David J. Whitehouse. Technological shifts in surface metrology. *Manufacturing Technology* 2012; 61(2):815-836.
- [3] T. Goto and K. Yanagi. An optimal discrete operator for the two-dimensional spline filter. *Measurement science and technology* 2009; 20(12):1-4. <http://dx.doi.org/10.1088/0957-0233/20/12/125105>
- [4] ASME B46.1-2009. Surface texture (surface roughness waviness, and lay). New York: American Society of Mechanical Engineers; 2010.
- [5] Y. Yuan, W. Piao, and J. Xu. A fast Gaussian filtering algorithm for three-dimensional surface roughness measurements. *Journal of Physics: conference Series International Symposium on Instrumentation Science and Technology*. 2006; 48:1401-1406.
- [6] M. Numada, T. Nomura, K. Kamiya, etc. Filter with variable transmission characteristics for determination of three-dimensional roughness. *Prec Eng* 2006; 30(4):431-442. <http://dx.doi.org/10.1016/j.precisioneng.2006.01.002>
- [7] ISO 16610-21. Geometrical product specifications (GPS)-filtration-part 21: linear profile filters: Gaussian filters; 2011.
- [8] H. Hanada, T. Saito, M. Hasegawa, and K. Yanagi. Sophisticated filtration technique for 3D surface topography data of rectangular area. *Wear* 2008; 264(5-6):422-427. <http://dx.doi.org/10.1016/j.wear.2006.08.035>
- [9] P. Perona and J. Malik. Scale-space and edge detection using anisotropic diffusion. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 12 (7): 629-639. <http://dx.doi.org/10.1109/34.56205>
- [10] ISO/TS 16610-22. Geometrical product specifications (GPS)-filtration-part 22: linear profile filters: spline filters; 2006.
- [11] H. Zhang, Y. B. Yuan, and W. Y. Piao. The spline filter: a regularization approach for the Gaussian filter. *Prec Eng* 2012; 36(4): 586-592. <http://dx.doi.org/10.1016/j.precisioneng.2012.04.008>
- [12] I. J. Schoenberg. Spline functions and the problem of graduation. *Proceedings of the National Academy of Sciences* 1964; 52: 947-950. <http://dx.doi.org/10.1073/pnas.52.4.947>
- [13] C. H. Reinsch. Smoothing by spline functions. *Numer. Math.* 1967; 10: 177-183. <http://dx.doi.org/10.1007/BF02162161>
- [14] T. Goto, J. Miyakura, and K. Umeda. A robust spline filter on the basis of L2-norm. *Prec Eng* 2005; 29(2):151-161. <http://dx.doi.org/10.1016/j.precisioneng.2004.06.004>
- [15] H. Zhang, Y. B. Yuan, J. Hua, and Y. Z. Cheng. High-Order Spline Filter: Design and Application to Surface Metrology. *Prec Eng* 2015; 40:74-80. <http://dx.doi.org/10.1016/j.precisioneng.2014.10.007>
- [16] M. Krystek. Form filtering by splines. *Measurement* 1996; 18(1):9-15. [http://dx.doi.org/10.1016/0263-2241\(96\)00039-5](http://dx.doi.org/10.1016/0263-2241(96)00039-5)
- [17] P. F. Johannes, D'haeyer. Gaussian filtering of images: a regularization approach. *Signal Processing* 1989; 18(2):169-181. [http://dx.doi.org/10.1016/0165-1684\(89\)90048-0](http://dx.doi.org/10.1016/0165-1684(89)90048-0)
- [18] Y. B. Yuan, X.F. Qiang, J. F. Song, and T. V. Vorburger. A fast algorithm for determining the Gaussian filtered mean line in surface metrology. *Prec Eng* 2000; 24(1):62-69. [http://dx.doi.org/10.1016/S0141-6359\(99\)00031-8](http://dx.doi.org/10.1016/S0141-6359(99)00031-8)
- [19] J. Raja, B. Muralikrishnan, and S. Fu. Recent advances in separation of roughness, waviness and form. *Prec Eng* 2002; 26(2):222-235. [http://dx.doi.org/10.1016/S0141-6359\(02\)00103-4](http://dx.doi.org/10.1016/S0141-6359(02)00103-4)
- [20] S. Brinkmann, H. Bodschiwinna, and H. W. Lemke. Accessing roughness in three-dimensions using Gaussian regression filtering. *Int. J. Mach. Tools Manuf* 2001; 41:2153-2161. [http://dx.doi.org/10.1016/S0890-6955\(01\)00082-7](http://dx.doi.org/10.1016/S0890-6955(01)00082-7)
- [21] J. Song and T. Vorburger. A novel parameter proposed for 2D and 3D topography measurements and comparisons. *Proc. SPIE* 6672, Advanced Characterization Techniques for Optics, Semiconductors, and Nanotechnologies III, August 26, 2007, San Diego.

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