applied optics

CHIMERA, a new holoprinter technology combining low-power continuous lasers and fast printing

YVES GENTET[1,*,†] AND PHILIPPE GENTET[2,†]

[1] Ultimate Holography, 33000 Bordeaux, France
[2] Plasma Bio Display, Kwangwoon University, Seoul 01897, South Korea
*Corresponding author: yves.gentet@ultimate-holography.com

Received 16 July 2019; revised 12 September 2019; accepted 13 September 2019; posted 13 September 2019 (Doc. ID 372858); published 0 MONTH 0000

This paper presents CHIMERA, a third-generation digital holographic printing system that solves the known problems of the two previous generations. This holoprinter is based on the use of low-power RGB continuous lasers combined with the ultrafine-grain silver-halide material Ultimate U04 and is capable of printing at a frequency equal to or greater than 25 hogels per second, full-color, 120° full-parallax digital reflection holograms or holographic optical elements with a size of up to 60 × 80 cm and a hogel size ranging from 250 to 500 μm. A 3D scanner using a 4K video camera has been specially designed for scanning real objects printable on CHIMERA, which offers new achievements in terms of color rendition, palette, and accuracy and opens new perspectives for digital holography applications and holography in general.

https://doi.org/10.1364/AO.99.099999

1. INTRODUCTION

Holography, invented in 1948 by physicist Dennis Gabor [1], is a 3D technique based on the interference and diffraction of light waves. Thanks to the progress made in recent years with the development of new diode-pumped solid-state (DPSS) lasers and new color recording materials—ultra-fine grain silver-halide emulsions and photopolymer materials—the last generation of a reflection analog Denisyuk hologram [2] is categorized as ultrarealistic because a spectator can hardly discriminate between the hologram and its real counterpart [3]. These holograms are full-color, with a full range of gray levels and a 180° full parallax, horizontally and vertically. While the holograms obtained have an extreme resolution due to the nanometric AgBr grain size of the silver-halide recording film, this Denisyuk technique has several limitations. For example, it is only possible to record a hologram of real and still objects and furthermore at the same scale. While this technique remains popular mainly for museum, artistic, or educational applications [4,5], it is inadequate enough to meet expectations of various fields such as advertising, military, architecture, automotive industry, medical, and entertainment.

To record virtual scenes of any size, digital holographic stereogram printing techniques have been developing since the end of the twentieth century and are now commonly used in various fields when analog holography cannot be used [6–8]. In 1995, Yamaguchi *et al.* [9] proposed a direct-write digital holography technique, using object and reference beams, to record a digital hologram divided into a matrix of small holographic elements or hogels [10]. In 1998, Klug *et al.* [11], from Zebra Imaging Inc (Austin, Texas, USA), developed this technique to propose the first commercial generation of large-format full-color reflection digital holographic printing systems. To record holograms, Zebra initially used high-power (several watts) continuous wave (CW) lasers and DuPont's color photopolymer material [12]. However, due to the mechanical vibration problems and the low sensitivity of DuPont's holographic material, Zebra holograms were printed at slow speed—around 2 hogels per second (or 2 Hz)—and with a rather large hogel size (800 μm). The direct printing on DuPont photopolymer gave holograms with a limited range of gray levels, keeping mostly the highlights. This slow printing speed was the main limitation of this first generation of holoprinters because a 60 × 60 cm print at a resolution of 800 μm took up to four days. Due to the use at that time of high-power CW lasers (krypton and argon gas lasers), the production was also costly in terms of both lasers, water, and electricity.

To overcome the speed problem, a second generation of holoprinters, using RGB pulsed lasers, was then developed by the Geola group (Vilnius, Lithuania) and XYZ Imaging Inc. (Montreal, Quebec, Canada) and then later by Yves Gentet (Bordeaux, France). The original idea of using pulsed lasers was proposed in 1999 by Brotherton-Ratcliffe *et al.* while working at Geola [13]. Pulsed-laser-based printers were printing fast (25 Hz) [14] on different silver-halide emulsion (Slavich [15] or Ultimate [16]) or photopolymer materials (DuPont or Covestro [17]). The RGB pulsed lasers emit beams at the following three primary wavelengths: 660 nm for red, 526 nm (or 532 nm) for green, and 440 nm for blue. Unfortunately, new problems absent from the first generation of holoprints then appeared. In particular, with these three specific wavelengths, the color accuracy of printed holograms was poor due to the weak sensitivity for eyes of the red and blue colors, when it was high for the green. Furthermore, due to the ultrafast exposures—nanosecond exposures compared with millisecond range with zebra technique—the diffraction efficiency (DE) of holograms was lower using pulsed lasers on all materials comparing equivalent recordings using the continuous lasers. Geola compensated partially for the lack of DE by reducing drastically the visible vertical parallax of their holograms compared with Zebra holograms. Furthermore, the manufacture of reliable pulsed lasers is a long and costly process, with their maintenance and the regular change of pumping lamps making them not perfectly reliable for commercial applications without having a laser specialist on call for the maintenance.

The purpose of our research project, which has lasted 15 years, has been to build a generation of holoprinter that would combine all the advantages of the two previous technologies while eliminating the known problems. When we accomplished this, the name CHIMERA was chosen to describe this new holoprinter technology, as it is now possible to achieve the improbable combination of low-power commercial low-cost CW lasers (from 20 mW) and fast printing (25 Hz typically). CHIMERA holograms are recorded on our in-house-developed silver-halide material Ultimate 04 (U04) [18] using a single custom full-color printing optical head having a circular parallax of 120°. This paper explains the CHIMERA technology and evaluates its performances.

2. CHIMERA OVERVIEW

A. Acquisition of Perspective Images and Hogel Generation

A half-parallax hologram is created by a recording of data thanks to a video camera (real or virtual for computer-generated [CG] objects), rotating around the scene, as shown in Fig. 1. These data are a series of a minimum of 192 and a maximum of 768 horizontal images—points of view of the scene—on a 120 deg arc of a circle. Video of half-parallax portraiture recording is presented in Visualization 1.

It is also possible to keep the camera static and use a rotating turntable stand for object recording. The camera always faces the center of the scene, which will be the center of the CHIMERA and at a constant distance from it. This system is the best-performing one due to the large visible parallax achieved. From these images, software is able to calculate all the hogels for the CHIMERA printing. On the hologram, the vertical camera's axis of rotation is the vertical axis of the holographic plate. Everything in front of this axis appears floating in front of the film plan.

A full-parallax hologram recording keeps the same requirements as for the half-parallax, but the procedure is repeated at

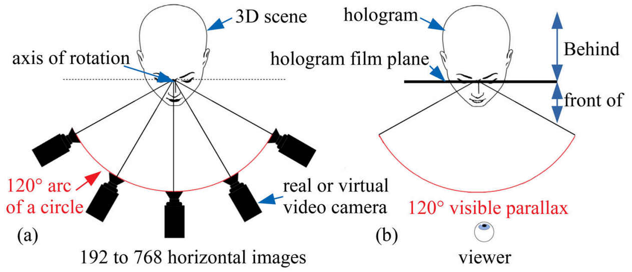

Fig. 1. (a) Acquisition of perspective images of a 3D scene for a half-parallax hologram. (b) What will be the printed hologram.

different levels of elevation—typically 48 to 192—creating a cylinder of points of view. This cylinder is equivalent to an H1 hologram in the traditional analog process. Acquisition of perspective images of the real 3D scenes is done with a custom 3D scanner, which has been specifically developed to work with the CHIMERA technology.

This scanner can record a still object scene from 10 × 13 cm to 60 × 80 cm with a 4K camera. The scanner records automatically until 768 (horizontal) × 192 (vertical) images, corresponding to a 120 × 52° perspective. Video of the 3D scanner in action is presented in Visualization 2. For CG objects, 3D computer graphics software 3DSmax was used with a custom script. The perspective images are generated into 3DSmax by moving a virtual camera, with exactly the same principles as leveraged for the analog scene (Fig. 2).

Then, software has been specifically developed for the CHIMERA printer to generate all the hogels in real time from the above perspective images according to the method described by Su *et al.* [19], at a speed higher than 50 Hz, which avoids the storage of heavy intermediate printing files.

B. Method to Print a CHIMERA

To print CHIMERA holograms, this new holoprinter uses three RGB low-power commercial CW DPSS lasers of a minimum of 20 mW. The wavelengths are 640, 532, and 457 nm. Three mechanical shutters allow adjustable exposures for each laser in the range of 1 to 2 ms. To avoid any movement of the holographic plate during the recording, a novel antivibrating mechanical system has been specially developed.

Each hogel is recorded one after another using an RGB display system made of three spatial light modulators (SLM) and a 120° custom-designed full-color optical printing head. After being interfered with a 45-deg reference—or zero-degree angle

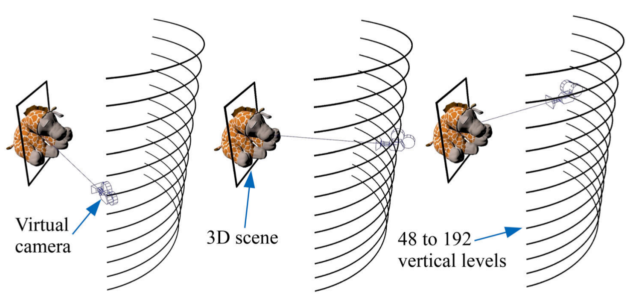

Fig. 2. Acquisition of perspective images of a 3D scene for a full-parallax hologram.

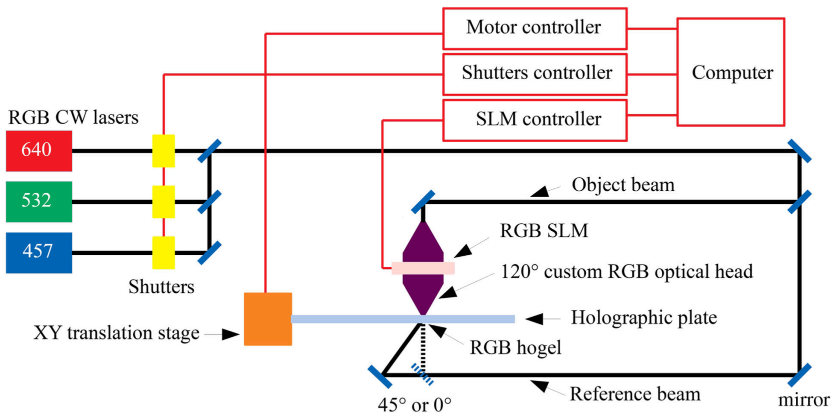

Fig. 3. Simplified schematic of the optical setup of CHIMERA printer system.

for map-style holograms—the information corresponding to each RGB hogel is recorded into the holographic recording material, one at a time.

A simplified schematic of the optical setup for the CHIMERA printer system is shown in Fig. 3. The hogel size can be chosen at 250 or 500 μm, the reference angle at 45° or 0°, and the printing rate from 1 to 50 Hz.

C. Material to Record and Develop CHIMERA

CHIMERA holograms were recorded on U04 silver-halide holographic glass plates. U04 is an isopanchromatic emulsion originally designed by the authors for recording full-color analog holograms using all the common visible laser wavelengths (442, 457, 473, 488, 514, 532, 633, 640, 647, and 660 nm). The grain size is so fine (4 nm) that any visible wavelength is recorded without diffusion. The minimum typical recommended exposure energy is in the range of per laser, for a full-color RGB hologram.

CHIMERA was then developed in two chemical baths, i.e., developer and bleach. These chemicals are safe for both holographers and the environment and are easy to use (Table 1). After processing, each CHIMERA is then sealed with a second glass plate and optical glue to protect the hologram and keep its colors constant in any environment.

D. Method to Illuminate CHIMERA After Processing

The choice of the final illumination source is important in full-color reflection holography because the reconstruction light must be a source point and content for the wavelengths of the original recording lasers. Commercial RGB LEDs currently offer the best solution [20] because their wavelengths are centered on the lasers' wavelengths.

To illuminate and reconstruct CHIMERA holograms, 3 Watt and 9 Watt RGB LEDs have been chosen depending on the size of the hologram and placed 50 cm from the center of the hologram at a 45 deg (or zero degree) angle.

Table 1. Ultimate 04 Processing Steps

Processing Steps	Time (min)
Develop in ultimate safe developer at 22°C	4
Wash under running water	0.5
Bleach in ultimate safe bleach at 22°C	Until clear
Wash under running water	3
Wash with a drop of wetting agent	1
Dry vertically	20

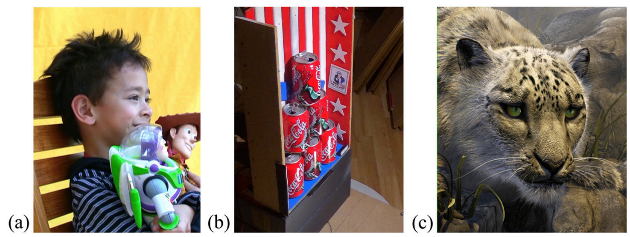

Fig. 4. (a) Recording of half-parallax portraits with a turning table. (b) Full-parallax still objects with the 3D scanner. (c) Full-parallax CG objects with 3DSmax scripting.

3. RESULTS

Acquisition of perspective images of a series of models was done: half-parallax portraits with a turning table [Fig. 4(a)]; full-parallax still objects with the 3D scanner [Fig. 4(b)]; and full-parallax CG objects with 3DSmax scripting [Fig. 4(c)].

Using the hogel-generation software, holograms were then printed on U04 glass plates at different sizes (10 × 13, 20 × 26, 30 × 40, and 60 × 80 cm), resolutions (250 and 500 μm) and printing speeds. When printing CHIMERA holograms with 500 μm hogels, it was possible to increase the printing speed up to 25 Hz vibrating. At 28 Hz, black hogels, as shown in Fig. 5,

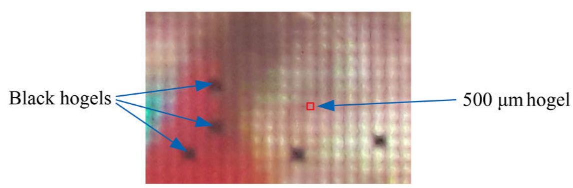

Fig. 5. Black hogel appears in case of vibration during the recording time.

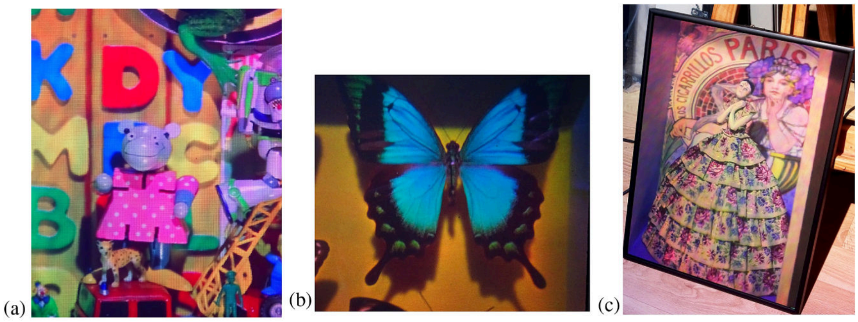

Fig. 6. Ultrarealistic CHIMERA recorded at different scales and resolutions. (a) An extract of a 30 × 40 cm (500 μm hogel) full-parallax CHIMERA of saturated color objects. (b) Extract of a 20 × 26 cm (250 μm hogel) full-parallax CHIMERA of natural butterflies. (c) 30 × 40 cm (500 μm hogel) full-parallax CHIMERA of a scanned museum pastel colors object.

Fig. 7. (a) Three different scans transferred into the same CHIMERA. (b) One scan given a two-channel gray-scale and full-color CHIMERA.

began to appear, indicating a vibration of the holographic plate during the recording period.

The duration of printing a hologram is decreased in proportion to a square law by reducing the hogel size, so a 250 μm hogel CHIMERA is four times longer to print than the same at 500 μm hogels. But, when printing CHIMERA holograms with 250 μm hogels, it was possible to increase the printing speed up to 50 Hz, so the global duration of printing was reduced by two only.

A series of ultrarealistic CHIMERA showing delicate and vivid colors, and even only gray levels (similar to black and white photographs), were recorded, as shown in Figs. 6 and 7. It was also possible to combine different images to record multichannel holograms, as shown in Fig. 7.

The colors' accuracy achieved on CHIMERA surpasses that obtained with printers using pulsed lasers, as shown in Figs. 8(a) and 8(b). As for the gray levels obtained, they have significantly greater tone definition than those of holograms made by a pulsed laser.

Results also confirm that the range of possible colors on a CHIMERA is greater than on an equivalent Denisyuk hologram (both recorded with the same RGB lasers). On a CHIMERA, the color balance of each point is defined by software, when, for a Denisyuk hologram, the color balance is a direct reading of the RGB component of each color. For example, yellow and gold colors are almost never correctly balanced on a Denisyuk hologram, when it is printed correctly on a CHIMERA, as shown in Fig. 9.

Videos showing the large visible parallax, and the color renditions of some CHIMERA holograms are presented in Visualization 3 and Visualization 4.

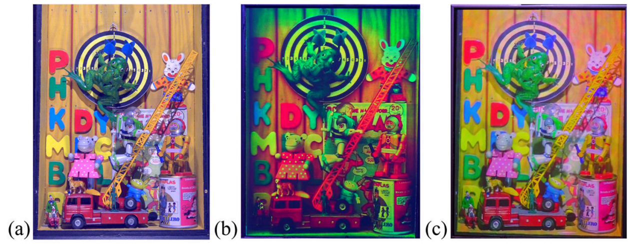

Fig. 8. (a) Same object scanned half-parallax in 2006 and printed with a second-generation printer—made by Yves Gentet—using RGB pulsed laser on (b) U08 and a 2019 full-parallax scan printed on CHIMERA printer on (c) U04.

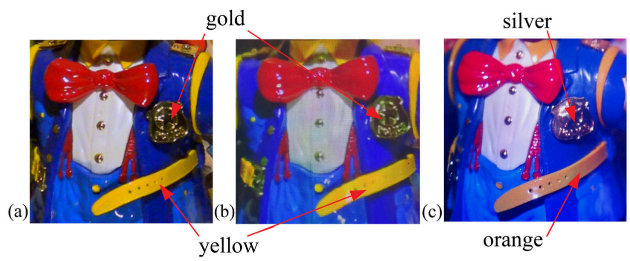

Fig. 9. Three photographs of (a) the real object, (b) the printed CHIMERA, and (c) the Denisyuk hologram. The color of the belt is yellow, and the color of the badge is gold for CHIMERA like the original object but appears orange and silver for the Denisyuk.

4. DISCUSSION

Moreover, while analog holograms have known scaling limitations—only real still objects and at 1:1 scale—Chimera can be printed at any scale, use CG images, and generate direct H2—pop-out images—which are the most fascinating for the public. Such H2 CHIMERA still keep a 120° full-parallax compared with traditional techniques of hologram transfer, which always have a reduction in the visible parallax.

Our in-house designed scanner allows the recording of real objects to create full-parallax holograms, without carrying *in situ* lasers, antivibrating system, holographic plates, and processing equipment. Furthermore, a CHIMERA hologram can be used as a master and be copied for mass replication applications with the same RGB CW lasers on both silver-halide and photopolymer materials.

The CHIMERA printer allows the printing of zero-degree horizontal images as Zebra introduced. However, Zebra holograms have had an asymmetrical $90 \times 70°$ visible full parallax, whereas CHIMERA is wider and symmetrical with 120 deg in all directions.

Comparing the Geola system using three RGB optical head, it is much more convenient and faster to use a full-color head only, as the machine does not need to print three times at the same hogel position.

The CHIMERA printer demonstrates at least the same printing speed as an existing pulsed-laser system. The overall printing time of a hologram is decreased in proportion to a square law by reducing the hogel size but is partially compensated by the increase of the speed of the CHIMERA printer, while a printer using a pulsed-laser system is always operating at the laser frequency. For example, at 500 μm hogel, the maximum printing speed is 25 Hz, and it takes 5 h 30 min to print a 30×40 cm hologram. At 250 μm hogel, the maximum printing speed is 50 Hz, and it takes 11 h to print a 30×40 cm hologram—instead of 22 h with an equivalent pulsed-laser system.

5. CONCLUSION

CHIMERA is a digital holographic printing system based on three low-power RGB CW lasers and Ultimate U04 ultrafine grain silver-halide holographic glass plates. The color rendition and the gray-level rendition greatly surpasses the quality of the two first generations of holoprinters. High-quality, highly diffractive, large-format, full-color, and full-parallax digital reflection holograms and HOEs can be recorded with a hogel resolution of 250 or 500 μm. The hogels' printing speed is high (25 Hz for 500 μm hogels and 50 Hz for 250 μm). At 250 μm hogel size, an observer can hardly detect a difference between an analog hologram and a CHIMERA. CHIMERA holograms have a mastering quality and can be copied with the same RGB CW lasers to produce copies on both silver-halide and photopolymer materials. The simplicity of the technology used with CHIMERA offers new perspectives for the development of color holography.

Acknowledgment. CHIMERA was first presented at the OSA Digital Holography and 3-D Imaging Conference 2019, Bordeaux, France.

[†]These authors contributed equally to this work.

REFERENCES

1. D. Gabor, "A new microscopic principle," Nature **161**, 777–778 (1948).
2. Y. N. Denisyuk, "On the reproduction of the optical properties of an object by the wave field of its scattered radiation," Opt. Spectrosc. **18**, 152–157 (1965).
3. H. Bjelkhagen and D. Brotherton-Ratcliffe, *Ultra-realistic imaging: advanced techniques in analogue and digital colour holography* (CRC press, 2016).
4. A. M. Sánchez, L. M. Giraldo, and D. V. Prieto, "Monocolor and color holography of pre-Hispanic Colombian goldwork: a way of Colombian heritage appropriation," Proc. SPIE **10558**, 1055803 (2018).
5. T. Voslion and A. Escarguel, "An easy physics outreach and teaching tool for holography," J. Phys. Conf. Ser. **415**, 012063 (2013).
6. H. Zheng, G. Sun, and Y. Yu, "A review of holographic printing technologies," Laser Optoelectron. Prog. **11**, 49 (2012).
7. M. Lucente, "The first 20 years of holographic video—and the next 20," in *SMPTE 2nd Annual International Conference on Stereoscopic 3D for Media and Entertainment* (2011), pp. 21–23.
8. J. Su, X. Yan, Y. Huang, X. Jiang, Y. Chen, and T. Zhang, "Progress in the synthetic holographic stereogram printing technique," Appl. Sci. **8**, 851 (2018).
9. M. Yamaguchi, T. Koyama, H. Endoh, N. Ohyama, S. Takahashi, and F. Iwata, "Development of full-parallax holoprinter," Proc. SPIE **2406**, 50–56 (1995).
10. M. Lucente, "Diffraction-specific fringe computation for electro-holography," Ph.D. dissertation (Massachusetts Institute of Technology, 1994).
11. M. Klug, M. Holdback, and A. Ferdman, "Method and apparatus for recording 1-step full-color full-parallax holographic stereograms," U.S. patent US6330088B1 (1998).
12. U. S. Rhee, H. J. Caulfield, C. S. Vikram, and J. Shamir, "Dynamics of hologram recording in DuPont photopolymer," Appl. Opt. **34**, 846–853 (1995).
13. D. C. Brotherton-Ratcliffe, F. M. Vergnes, A. Rodin, and M. Grichine, "Method and apparatus to print holograms," Lithuanian patent LT4842 (1999).
14. D. C. Brotherton-Ratcliffe, S. J. Zacharovas, R. J. Bakanas, J. Pileckas, A. Nikolskij, and J. Kuchin, "Digital holographic printing using pulsed RGB lasers," Opt. Eng. **50**, 091307 (2011).
15. "Slavich," 2019, https://www.slavich.com (July).
16. Y. Gentet and P. Gentet, "Ultimate emulsion and its applications: a laboratory-made silver halide emulsion of optimized quality for monochromatic pulsed and full-color holography," Proc. SPIE **4149**, 56–62 (2000).
17. Covestro Deutschland AG, Bayfol HX200 Datasheet (2018).
18. P. Gentet, Y. Gentet, and S. H. Lee, "Ultimate 04 the new reference for ultra-realistic color holography," International Conference on Emerging Trends & Innovation in ICT (ICEI) **1**, 162–166 (2017).
19. J. Su, Q. Yuan, Y. Huang, X. Jiang, and X. Yan, "Method of single-step full parallax synthetic holographic stereogram printing based on effective perspective images' segmentation and mosaicking," Opt. Express **25**, 23523–23544 (2017).
20. P. Gentet, Y. Gentet, and S. H. Lee, "New LED's wavelengths improve drastically the quality of illumination of pulsed digital holograms," in *Digital Holography and Three-Dimensional Imaging* (Optical Society of America, 2017), pp. M3A-4.

Query

1. AU: You did not provide funding information to OSA at the time of article submission. If this article was funded by one or more organization(s)/institutions(s), please provide the full name of that entity as provided in the Open Funder Registry (https://search.crossref.org/funding) and all pertinent grant/contract/project/award numbers.