METHODS AND SYSTEMS FOR SELECTING PARAMETERS TO APPROXIMATE DESIRED PROPERTIES OF STRUCTURAL COLOR

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority to U.S. Provisional Patent Application No. 62/984,582, filed March 3, 2020, entitled "Methods and Systems for Selecting Parameters to Approximate Desired Properties of Structural Color," the disclosure of which is incorporated herein by reference in its entirety, and to U.S. Provisional Application No. 63/050,946, filed on July 13, 2020, entitled "Methods and Systems for Selecting Parameters to Approximate Desired Properties of Structural Color," the disclosure of which is incorporated herein by reference in its entirety.

BACKGROUND

[0001] Structural color relies on the physical properties of a material to produce color. These physical properties give rise to interference among scattered light waves, which gives the scattered light a particular color. This makes structural color different from other types of color that rely on the chemical properties of the material.

[0002] Although structural color is common in nature, it has been difficult to reproduce by conventional techniques. Among other reasons, there is an extremely large number of configurations of physical properties that can affect the way that light scatters from a surface. Moreover, when the light scatters from the surface, the interference effects can be hard to predict because of the complex ways that the light interacts with the material and with itself. These problems make it difficult to identify a specific set (or sets) of properties that will give rise to a specific desired structural color.

SUMMARY

[0003] There is need for the ability to reliably predict the structural color of particles and materials. Further, there is a need for the ability to design particles and physical properties of materials according to desired optical properties. The exemplary ~~embodiments~~ examples provide methods, mediums, and systems for selecting and designing parameters of a nanoparticle or nanoparticle array that result in desired optical properties for structural color of the nanoparticle array.

[0004] According to one ~~aspect~~example, there is a method for determining an optical output parameter indicative of structural color. The method may include: providing, to a processor of a

simulation system, one or more input properties, wherein each of the one or more input properties is indicative of a property of an array of nanoparticles; providing, to the processor, one or more input parameters for an optical simulation; performing, by the processor, the optical simulation by applying a stochastic model of the array of nanoparticles according to the input parameters; and determining, by the processor, and from the optical simulation, an output optical parameter indicative of structural color.

[0004a] In an aspect, there is provided a method comprising:

providing, to a processor of a simulation system, one or more input properties, wherein each of the one or more input properties is indicative of a property of one or more arrays of nanoparticles, and wherein each of the arrays of nanoparticles is contained within one of a plurality of microspheres, and wherein the plurality of microspheres is contained within a bulk material;

providing, to the processor, one or more input parameters for an optical simulation;

performing, by the processor, the optical simulation by applying a stochastic model of the array of nanoparticles according to the input parameters, wherein the optical simulation accounts for properties of light as applied to the bulk material and microspheres thereof; and

determining, by the processor, and from the optical simulation, an output optical parameter indicative of structural color.

[0005] In another ~~aspect~~example, there is a simulation system for determining structural color. The system may include a processor configured to execute machine readable instructions that cause the processor to: receive one or more input properties, wherein each of the one or more input properties is indicative of a property of an array of nanoparticles; receive one or more input parameters for an optical simulation; perform the optical simulation by applying a stochastic model of the array of nanoparticles according to the input parameters; and determine from the optical simulation an output optical parameter indicative of structural color.

[0005a] In another aspect, there is provided a simulation system for determining structural color, the system comprising a processor configured to execute machine readable instructions that cause the processor to:

receive one or more input properties, wherein each of the one or more input properties is indicative of a property of an array of nanoparticles, the array of nanoparticles being part of a

bulk material, the bulk material including at least one microsphere containing the array of nanoparticles;

receive one or more input parameters for an optical simulation;

perform the optical simulation by applying a stochastic model of the array of nanoparticles according to the input parameters, wherein the optical simulation accounts for properties of light as applied to the bulk material; and

determine from the optical simulation an output optical parameter indicative of structural color.

[0006] In yet another ~~aspect~~example, there is a method for determining one or more properties of an array of nanoparticles according to desired target properties. The method may include: providing, to a processor, one or more target properties, wherein each of the one or more target properties is indicative of a desired optical property of an array of nanoparticles; providing, to the processor, one or more input parameters for an optical simulation; performing, by the processor, an evolutionary algorithm according to the input properties and input parameters, and wherein the evolutionary algorithm employs an optical simulation of the array of nanoparticles; and determining, by the processor, and from the evolutionary algorithm, an output design parameter indicative of one or more properties of the array of nanoparticles.

[0007] In still another ~~aspect~~example, there is an optimization system. The optimization system may include a processor configured to execute machine readable instructions that cause the processor to: receive one or more target properties, wherein each of the one or more target properties is indicative of a desired optical property of an array of nanoparticles; receive one or more input parameters for an optical simulation; perform an evolutionary algorithm according to the input properties and input parameters, and wherein the evolutionary algorithm employs an optical simulation of the array of nanoparticles; and determine an output design parameter from the evolutionary algorithm, the output design parameter being indicative of one or more properties of the array of nanoparticles.

CLAIMS

What is claimed is:

1. A method comprising:

providing, to a processor of a simulation system, one or more input properties, wherein each of the one or more input properties is indicative of a property of one or more arrays of nanoparticles, and wherein each of the arrays of nanoparticles is contained within one of a plurality of microspheres, and wherein the plurality of microspheres is contained within a bulk material;

providing, to the processor, one or more input parameters for an optical simulation;

performing, by the processor, the optical simulation by applying a stochastic model of the array of nanoparticles according to the input parameters, wherein the optical simulation accounts for properties of light as applied to the bulk material and microspheres thereof; and

determining, by the processor, and from the optical simulation, an output optical parameter indicative of structural color.

2. The method of claim 1, wherein the one or more input properties comprise one or more of a structural property of the one or more arrays of nanoparticles and an optical property of the one or more arrays of nanoparticles.

3. The method of claim 2, wherein the structural property of the one or more arrays of nanoparticles comprises one or more of a nanoparticle size, a nanoparticle shape, a nanoparticle material, a nanoparticle porosity, a surface feature of a nanoparticle, a lattice constant of a plurality of nanoparticles, a concentration of nanoparticles in a medium, a void size of a nanoparticle, a property of a direct structure, a property of an inverse structure, a property of an ordered structure, a property of a disordered structure, a size of a microsphere of the array of nanoparticles, a shape of a microparticle composed of the at least one array of nanoparticles, a nanoparticle polydispersity, a shell thickness, a shell material, a concentration of microspheres in the bulk material, and a thickness of the bulk material.

4. The method of claim 2, wherein the optical parameter of the one or more arrays of nanoparticles comprises one or more of a real index of refraction, a complex index of

refraction, an absorption value, a dispersion value, a birefringence, a polarization, a nonlinear coefficient.

5. The method of claim 1, wherein the one or more output optical parameters comprises one or more of a wavelength, range of wavelengths, reflection curve, transmission curve, absorption curve, a speckle amount, a scattering parameter, an angle dependence, and angle independence.

6. The method of claim 1, wherein the stochastic model comprises a Monte Carlo model.

7. The method of claim 1, wherein the stochastic model comprises a two-tiered stochastic model.

8. The method of claim 1, wherein the one or more input properties comprises one or more medium parameters.

9. The method of claim 7, wherein the one or more medium parameters comprises one or more of a material, a complex refractive index of the medium, a microsphere concentration, a microsphere mixture, an absorber amount, an absorber concentration, a thickness of the array of nanoparticles, or a degree of order of the array of nanoparticles

10. The method of claim 1, further comprising producing the bulk material, wherein the bulk material includes at least one of a dye, a paint, or a coating comprising the one or more arrays of nanoparticles.

11. A simulation system for determining structural color, the system comprising a processor configured to execute machine readable instructions that cause the processor to:

receive one or more input properties, wherein each of the one or more input properties is indicative of a property of an array of nanoparticles, the array of nanoparticles being part of a bulk material, the bulk material including at least one microsphere containing the array of nanoparticles;

receive one or more input parameters for an optical simulation;

perform the optical simulation by applying a stochastic model of the array of nanoparticles according to the input parameters, wherein the optical simulation accounts for properties of light as applied to the bulk material; and

determine from the optical simulation an output optical parameter indicative of structural color.

12. The system of claim 11, wherein the one or more input properties comprise one or more of a structural property of the array of nanoparticles and an optical property of the array of nanoparticles.

13. The system of claim 12, wherein the structural property of the array of nanoparticles comprises one or more of a nanoparticle size, a nanoparticle shape, a nanoparticle material, a nanoparticle porosity, a surface feature of a nanoparticle, a lattice constant of an array of nanoparticles, a concentration of nanoparticles in a medium, a void size of a nanoparticle, a property of a direct structure, a property of an inverse structure, a property of an ordered structure, a property of a disordered structure, a nanoparticle polydispersity, a shell thickness, a shell material, a concentration of microspheres in the bulk material, and a thickness of the bulk material.

14. The system of claim 12, wherein the optical parameter of the array of nanoparticles comprises one or more of a real index of refraction, a complex index of refraction, an absorption value, a dispersion value, a birefringence, a polarization, and a nonlinear coefficient.

15. The system of claim 11, wherein the one or more output optical parameters comprises one or more of a wavelength, range of wavelengths, reflection curve, transmission curve, absorption curve, a speckle amount, a scattering parameter, an angle dependence, and angle independence.

16. The system of claim 11, wherein the stochastic model comprises a Monte Carlo model.

17. The system of claim 11, wherein the one or more input properties comprises one or more medium parameters.

18. The system of claim 17, wherein the one or more medium parameters comprises one or more of a material, a complex refractive index of the medium, a microsphere concentration, a microsphere mixture, an absorber amount, an absorber concentration, a thickness of the array of nanoparticles, or a degree of order of the array of nanoparticles

19. The system of claim 11, further comprising a manufacturing device configured to produce the bulk material, wherein the bulk material includes at least one of a dye, paint, or coating including the array of nanoparticles.

~~20. A method comprising:~~

~~providing, to a processor, one or more target properties, wherein each of the one or more target properties is indicative of a desired optical property of an array of nanoparticles, the array of nanoparticles being part of a bulk material, wherein the bulk material includes at least one microparticle containing the array of nanoparticles;~~

~~providing, to the processor, one or more input parameters for an optical simulation;~~

~~performing, by the processor, an evolutionary algorithm according to the input properties and input parameters, wherein the evolutionary algorithm employs an optical simulation of the array of nanoparticles, and wherein the optical simulation accounts for properties of light as applied to the bulk material; and~~

~~determining, by the processor, and from the evolutionary algorithm, an output design parameter indicative of one or more properties of the array of nanoparticles.~~

~~21. The method of claim 20, wherein the one or more properties of the array of nanoparticles comprises one or more of a nanoparticle size, a nanoparticle shape, a nanoparticle material, a nanoparticle porosity, a surface feature of a nanoparticle, a lattice constant of an array of nanoparticles, a concentration of nanoparticles in a medium, a nanoparticle polydispersity, a shell thickness, a shell material, a concentration of microspheres in the bulk material, and a thickness of the bulk material.~~

~~22. The method of claim 20, wherein the one or more target properties indicative of a desired optical property comprises one or more of a wavelength, a range of wavelengths, a reflection curve, a transmission curve, an absorption curve, a speckle amount, a scattering parameter, a target transport length, a structural color, an angle dependence, and an angle independence.~~

~~23. The method of claim 20, further comprising producing the bulk material, wherein the bulk material includes at least one of a dye, a paint, or a coating comprising the array of nanoparticles having the output structural design parameters.~~

24. The method of claim 20, wherein the evolutionary algorithm comprises one of a maximum likelihood optimization, a differential evolution algorithm, a Bayesian optimization, genetic algorithm, a covariance matrix adaptation evolution strategy, a particle swarm optimization, and simulated annealing.

25. The method of claim 20, wherein the one or more input parameters comprises a medium parameter including one or more of a type of a medium, a complex refractive index of the medium, a microsphere concentration, a microsphere mixture, an absorber amount, an absorber concentration, a property of the absorber, a thickness of the array of nanoparticles, array of nanoparticles, thickness of a bulk material made up of microspheres, or a degree of order of the array of nanoparticles.

26. The method of claim 20, wherein the one or more input parameters comprises a manufacturing parameter that includes a limitation on at least one parameter of one or more of a include one or more properties of the array of nanoparticles, a structural property of the array of nanoparticles, an optical property of the array of nanoparticles, or a medium parameter.

27. The method of claim 20, wherein the evolutionary algorithm further applies one or more of box constraints and soft constraints to one of the input properties or input parameters.

28. The method of claim 20, wherein determining the output design parameter further comprises:

stopping, by the processor, the evolutionary algorithm upon satisfying a stop condition; and

storing, by the processor, the output design parameter in a non-transitory memory.

29. The method of claim 28, wherein the stop condition comprises one of performing a predetermined number of iterations, elapsing of a predetermined amount of time, a predefined threshold of a rate of change of the objective function, a determination of stagnation of the objective function over a predefined number of iterations, and a threshold value of the objective function.

30. A optimization system comprising a processor configured to execute machine readable instructions that cause the processor to:

receive one or more target properties, wherein each of the one or more target properties is indicative of a desired optical property of an array of nanoparticles, the array of nanoparticles being part of a bulk material, wherein the bulk material includes a microsphere containing the array of nanoparticles;

receive one or more input parameters for an optical simulation;

perform an evolutionary algorithm according to the input properties and input parameters, wherein the evolutionary algorithm employs an optical simulation of the array of nanoparticles, and wherein the optical simulation accounts for properties of light as applied to the bulk material; and

determine an output design parameter from the evolutionary algorithm, the output design parameter being indicative of one or more properties of the array of nanoparticles.

31. The optimization system of claim 30, wherein the one or more properties of the array of nanoparticles comprises one or more of a nanoparticle size, a nanoparticle shape, a nanoparticle material, a nanoparticle porosity, a surface feature of a nanoparticle, a lattice constant of the array of nanoparticles, a concentration of nanoparticles in a medium, a nanoparticle polydispersity, a shell thickness, a shell material, a concentration of microspheres in the bulk material, and a thickness of the bulk material.

32. The optimization system of claim 30, wherein the one or more target properties indicative of a desired optical property comprises one or more of a wavelength, a range of wavelengths, a reflection curve, a transmission curve, an absorption curve, a speckle amount, a scattering parameter, a target transport length, a structural color, an angle dependence, and angle independence.

33. The optimization system of claim 30, further comprising a manufacturing device configured to produce the bulk material, wherein the bulk material includes at least one of a dye, paint, or coating including the array of nanoparticles.

34. The optimization system of claim 30, wherein the evolutionary algorithm comprises one of a maximum likelihood optimization, a differential evolution algorithm, a Bayesian optimization, a genetic algorithm, a covariance matrix adaptation evolution strategy, a particle swarm optimization, and simulated annealing.

~~35. The optimization system of claim 30, wherein the one or more input parameters comprises a medium parameter including one or more of a type of a medium, a complex refractive index of the medium, a microsphere concentration, a microsphere mixture, an absorber amount, an absorber concentration, a property of the absorber, a thickness of the array of nanoparticles, array of nanoparticles, thickness of a bulk material made up of microspheres, or a degree of order of the array of nanoparticles.~~

~~36. The optimization system of claim 30, wherein the one or more input parameters comprises a manufacturing parameter that includes a limitation on at least one parameter of the array of nanoparticles including one or more of a structural property of the array of nanoparticles, an optical property of the array of nanoparticles, or a medium parameter.~~

~~37. The optimization system of claim 30, wherein the evolutionary algorithm further applies one or more of box constraints and soft constraints to one of the input properties or input parameters.~~

~~38. The optimization system of claim 30, wherein to determine the output design parameter the machine readable instructions further cause the processor to:~~

~~stop the evolutionary algorithm upon satisfying a stop condition; and~~

~~store the output design parameter in a non-transitory memory.~~

~~39. The optimization system of claim 38, wherein the stop condition comprises one of performing a predetermine number of iterations, elapsing of a predetermined amount of time, a predefined threshold of a rate of change of the objective function, a determination of stagnation of the objective function over a predefined number of iterations, and a threshold value of the objective function.~~