

METHOD AND SYSTEM FOR IMAGE STITCHING

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority of Singapore Patent Application No. 10202101896X, filed on 24 February 2021, the content of which being hereby incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD

[0002] The present invention generally relates to a method and a system for image stitching.

BACKGROUND

[0003] Image stitching is utilized in various visual applications, such as panorama imaging and object insertion. The stitching quality may be measured or judged visually by the similarity of the stitched image (which may also be referred as a composite or final image) with respect to the input images (which may also be referred to as base or original images) from which the stitched image was formed, and by the visibility of any seam in the stitched image.

[0004] For example, a panoramic image is usually formed from multiple images captured at a single location with slightly different viewpoints for a wide-angle representation of a scene. The multiple captured images are first geometrically aligned and then stitched together to form the stitched image. In this regard, it is desirable for the stitched image to be as accurate and as natural (or realistic) as possible with respect to the input images, both geometrically and photometrically. For example, it is desirable for the stitched image to be seamless, that is, no seams visible in the stitched image such as at regions thereof formed by overlapping regions of the input images. In addition, it is desirable for there to be no visible color tones change from one region to another region of the stitched image.

[0005] Due to the visual richness on panoramas, various commercial applications have been developed to provide panoramic image stitching functions. At the same time, with the increasing processing power of mobile devices, panorama imaging mode has been embedded in many smart phones and digital cameras.

[0006] Optimal seam finding is one typical conventional approach for stitching multiple input images after all of the input images have been geometrically aligned. Conventional optimal seam finding techniques (or algorithms) search for an optimal seam in an overlapping region of adjacent input images so that differences between two adjacent images along the

optimal seam in the overlapping region can be minimized. For example, the optimal seam may be found or determined by a graph-cut, dynamic programming or other techniques. An advantage of optimal seam finding is its low computational and memory cost. However, it is very sensitive to photometric inconsistency, which appears as a global intensity or color difference in the stitched image between different regions thereof corresponding to different input images due to changes of scene illumination and camera responses. Therefore, a key problem of optimal seam finding is that seams may be visible and artifacts may arise in the stitched image (e.g., the final panoramic image).

[0007] Transition smoothing is another typical conventional approach for stitching multiple input images. It can reduce the seam artifacts in the stitched image by smoothing the transition between input images. As an example approach, alpha blending may be employed to blend (or combine) all of the input images based on weighted averaging. In this regard, the weighting coefficients may vary spatially as a function of the distance from the seam. As another example, pyramid blending may be employed to blend all of the input images in multiple scales, and different scale bands are combined with different blending masks. Accordingly, these two conventional approaches focus on smoothing the transition in the vicinity of the overlapping region (or area) of input images. However, if the illumination and color differences among the input images are large, although seams may be smoothed to almost invisible, the color tones change from one region (or area) to another region shown on the stitched image (e.g., the final panoramic image) may result in the stitched image looking unnatural. In this regard, color correction may be employed before the stitching process to balance colors and luminance in the whole image sequence. Unfortunately, all these conventional methods may only reduce the color tones change from one region to another region.

[0008] Instead of image stitching in the image domain as discussed above, in a different approach or direction, there has been disclosed image stitching in the gradient domain, which may be referred to as a conventional gradient domain stitching process (or technique). In this conventional approach, the gradient fields of all of the input images are first blended via an alpha blending to form a guidance vector field. The stitched image may then be generated by solving a Poisson equation with boundary conditions. Although conventional gradient domain approaches may reduce artifacts, they require large computational cost and memory consumption.

[0009] A need therefore exists to provide a method and a system for image stitching, that seek to overcome, or at least ameliorate, one or more problems associated with conventional

methods and systems for image stitching, and in particular, to enhance or improve effectiveness (e.g., produce a more accurate and natural (or realistic) stitched image, e.g., without visible seams and without visible color tones change from one region to another region of the stitched image) and/or efficiency (e.g., reduced computational costs and memory consumption, e.g., compared to conventional gradient domain approaches) in image stitching.

SUMMARY

[0010] According to a first aspect of the present invention, there is provided a method of image stitching using at least one processor, the method comprising:

- 10 generating a first stitched image based on a plurality of input images and based on an image domain stitching process;
- generating a guidance vector field based on a plurality of gradient fields of the plurality of input images and based on a gradient domain stitching process; and
- generating a second stitched image based on solving a first optimization problem based
- 15 on the first stitched image and the guidance vector field.

[0011] According to a second aspect of the present invention, there is provided a system for image stitching, the system comprising:

- a memory; and
- at least one processor communicatively coupled to the memory and configured to:
- 20 generate a first stitched image based on a plurality of input images and based on an image domain stitching process;
- generate a guidance vector field based on a plurality of gradient fields of the plurality of input images and based on a gradient domain stitching process; and
- generate a second stitched image based on solving a first optimization problem
- 25 based on the first stitched image and the guidance vector field.

[0012] According to a third aspect of the present invention, there is provided a computer program product, embodied in one or more non-transitory computer-readable storage mediums, comprising instructions executable by at least one processor to perform a method of image stitching, the method comprising:

- 30 generating a first stitched image based on a plurality of input images and based on an image domain stitching process;
- generating a guidance vector field based on a plurality of gradient fields of the plurality of input images and based on a gradient domain stitching process; and

generating a second stitched image based on solving a first optimization problem based on the first stitched image and the guidance vector field.

BRIEF DESCRIPTION OF THE DRAWINGS

5 [0013] Embodiments of the present invention will be better understood and readily apparent to one of ordinary skill in the art from the following written description, by way of example only, and in conjunction with the drawings, in which:

FIG. 1 depicts a schematic flow diagram of a method of image stitching, according to various embodiments of the present invention;

10 FIG. 2 depicts a schematic block diagram of a system for image stitching, according to various embodiments of the present invention;

FIG. 3 depicts a schematic block diagram of an exemplary computer system which may be used to realize or implement the system for image stitching, according to various embodiments of the present invention;

15 FIGS. 4A to 4C depict images for a comparison between the present image domain stitching method and the present hybrid image stitching method according to various example embodiments of the present invention,

FIGS. 5A to 5D depict images for a comparison between the present hybrid image stitching method according to various example embodiments of the present invention and two
20 conventional image stitching algorithms in the case of the input images having similar exposure level;

FIGS. 6A to 6D depict images for a comparison between the present hybrid image stitching method according to various example embodiments of the present invention and two
25 conventional image stitching algorithms in the case of the input images having significantly different exposure level;

FIGS. 7A to 7D depict images for a comparison amongst a conventional image stitching algorithm, the present image domain stitching algorithm and the present hybrid image stitching algorithm according to various example embodiments of the present invention; and

30 FIG. 8 depicts a stitched image generated by the present hybrid image stitching algorithm from the input images shown in FIG. 4A with the value of λ set as 16, according to various example embodiments of the present invention.

DETAILED DESCRIPTION

[0014] Various embodiments of the present invention provide a method and a system for image stitching. For example, as described in the background, conventional image domain approaches for image stitching may result in color tones change from one region (or area) to another region shown on the stitched image, thereby resulting in the stitched image looking unnatural. On the other hand, conventional gradient domain approaches for image stitching require large computational cost and memory consumption, thereby resulting in inefficiencies in image stitching. Accordingly, various embodiments of the present invention provide a method and a system for image stitching, that seek to overcome, or at least ameliorate, one or more problems associated with conventional methods and systems for image stitching, and in particular, to enhance or improve effectiveness (e.g., produce a more accurate and natural (or realistic) stitched image, e.g., without visible seams and without visible color tones change from one region to another region of the stitched image) and/or efficiency (e.g., reduced computational costs and memory consumption, e.g., compared to conventional gradient domain approaches) in image stitching.

[0015] FIG. 1 depicts a schematic flow diagram of a method 100 of image stitching using at least one processor, according to various embodiments of the present invention. The method 100 comprises: generating (at 102) a first stitched image based on a plurality of input images and based on an image domain stitching process; generating (at 104) a guidance vector field based on a plurality of gradient fields of the plurality of input images (respectively) and based on a gradient domain stitching process; and generating (at 106) a second stitched image (e.g., a final or output stitched image) based on solving a first optimization problem based on the first stitched image and the guidance vector field.

[0016] Accordingly, the method 100 of image stitching has advantageously been found to enhance or improve effectiveness and/or efficiency in image stitching. In particular, by performing image stitching in both the image and gradient domains and solving an optimization problem involving both the image and gradient domains simultaneously to obtain a final (or output) stitched image, the input images have been found to be effectively stitched to generate a more accurate and natural (or realistic) final stitched image that is without (or at least not obvious or easily noticeable) visible seams and without (or at least not obvious or easily noticeable) visible color tones change from one region to another region of the final stitched image. Furthermore, as will be described later below, the optimization problem is also capable

of being solved using a fast method, thereby significantly improving the efficiency in image stitching. These advantages or technical effects, and/or other advantages or technical effects, will become more apparent to a person skilled in the art as the method 100 of image stitching, as well as the corresponding system for image stitching, is described in more detail according to various embodiments and example embodiments of the present invention.

[0017] In various embodiments, the first optimization problem is configured as a cost function comprising an image domain function and a gradient domain function. In various embodiments, the image domain function is defined in an image domain based on the first stitched image. In various embodiments, the gradient domain function is defined in a gradient domain and based on the guidance vector field.

[0018] In various embodiments, the image domain function is configured to provide a measure of fidelity (e.g., closeness) between the second stitched image and the first stitched image. In various embodiments, the gradient domain function is configured to provide a measure of fidelity (e.g., closeness) between a gradient field of the second stitched image and the guidance vector field.

[0019] In various embodiments, the above-mentioned solving the first optimization problem comprises: decomposing the cost function into a plurality of spatial dimensions associated with the second stitched image to obtain a plurality of one-dimensional (1D) cost functions, respectively; and solving, for each of the plurality of 1D cost functions, the 1D cost function based on solving a corresponding linear equation.

[0020] In various embodiments, the method 100 further comprises geometrically aligning the plurality of input images to produce a plurality of aligned input images. In this regard, the above-mentioned generating (at 102) the first stitched image based on the plurality of input images is based on the plurality of aligned input images, and the above-mentioned generating (at 104) the guidance vector field based on the plurality of gradient fields of the plurality of input images is based on a plurality of gradient fields of the plurality of aligned input images.

[0021] In various embodiments, the method 100 further comprises: converting the plurality of input images from Red, Green and Blue (RGB) color space to Luminance-Bandwidth-Chrominance (YUV) color space; and adjusting, for each of the plurality of input images (e.g., the plurality of aligned input images), a luminance component of the input image based on a correction parameter (e.g., optimal gamma correction parameter) determined for the input image to produce a color corrected input image so as to obtain a plurality of color corrected input images. In this regard, the above-mentioned generating (at 102) the first stitched image

based on the plurality of input images is based on the plurality of color corrected input images, and the above-mentioned generating (at 104) the guidance vector field based on the plurality of gradient fields of the plurality of input images is based on a plurality of gradient fields of the plurality of color corrected input images.

5 **[0022]** In various embodiments, the method 100 further comprises determining a plurality of correction parameters (i.e., the above-mentioned correction parameter) for the plurality of input images, respectively, based on solving a second optimization problem configured for matching, for each pair of adjacent input images (immediately adjacent input images) amongst the plurality of input images having an overlapping region therebetween, the luminance
10 components of the pair of adjacent input images in the overlapping region thereof.

[0023] In various embodiments, the above-mentioned generating (at 102) the first stitched image comprises: for each pair of adjacent input images (immediately adjacent input images) amongst the plurality of input images having an overlapping region therebetween, determining a pixel value of each pixel of the first stitched image in the overlapping region based on a
15 weighted combination (e.g., based on a weighting factor determined) of corresponding pixels of the pair of adjacent input images. In this regard, corresponding pixels of a pair of adjacent input images with respect to a pixel of the first stitched image refer to a corresponding pixel of an image input and a corresponding pixel of the other image input of the pair of adjacent input images corresponding to the pixel of the first stitched image.

20 **[0024]** In various embodiments, the above-mentioned generating (at 104) the guidance vector field comprises: for each pair of adjacent input images (immediately adjacent input images) amongst the plurality of input images having an overlapping region therebetween, determining a gradient at each pixel of the guidance vector field (e.g., at each portion of the guidance vector field corresponding to corresponding pixels of the pair of adjacent input
25 images) in the overlapping region based on a weighted combination of gradients at corresponding pixels of the pair of adjacent input images. In this regard, similarly, corresponding pixels of a pair of adjacent input images with respect to a pixel of the guidance vector field refer to a corresponding pixel of an image input and a corresponding pixel of the other image input of the pair of adjacent input images corresponding to the pixel of the guidance
30 vector field.

[0025] In various embodiments, the above-mentioned generating (at 104) the guidance vector field further comprises adjusting (e.g., tuning) the guidance vector field based on a

plurality of correction parameters (i.e., the above-mentioned correction parameter) determined for the plurality of input images, respectively.

[0026] FIG. 2 depicts a schematic block diagram of a system 200 for image stitching, according to various embodiments of the present invention, corresponding to the method 100 of image stitching as described hereinbefore with reference to FIG. 1 according to various embodiments of the present invention. The system 200 comprises: a memory 202; and at least one processor 204 communicatively coupled to the memory 202 and configured to perform the method 100 of image stitching as described herein according to various embodiments of the present invention. Accordingly, in various embodiments, the at least one processor 204 is configured to: generate a first stitched image based on a plurality of input images and based on an image domain stitching process; generate a guidance vector field based on a plurality of gradient fields of the plurality of input images and based on a gradient domain stitching process; and generate a second stitched image based on solving a first optimization problem based on the first stitched image and the guidance vector field.

[0027] It will be appreciated by a person skilled in the art that the at least one processor 204 may be configured to perform various functions or operations through set(s) of instructions (e.g., software modules) executable by the at least one processor 204 to perform various functions or operations. Accordingly, as shown in FIG. 2, the system 200 may comprise a first stitched image generating module (or a first stitched image generating circuit) 206 configured to generate a first stitched image based on a plurality of input images and based on an image domain stitching process; a guidance vector field generating module (or a guidance vector field generating circuit) 208 configured to generate a guidance vector field based on a plurality of gradient fields of the plurality of input images and based on a gradient domain stitching process; and a second stitched image generating module (or a second stitched image generating circuit) 210 configured to generate a second stitched image based on solving a first optimization problem based on the first stitched image and the guidance vector field.

[0028] It will be appreciated by a person skilled in the art that the above-mentioned modules are not necessarily separate modules, and one or more modules may be realized by or implemented as one functional module (e.g., a circuit or a software program) as desired or as appropriate without deviating from the scope of the present invention. For example, two or more of the first stitched image generating module 206, the guidance vector field generating module 208 and second stitched image generating module 210 may be realized (e.g., compiled together) as one executable software program (e.g., software application or simply referred to

as an “app”), which for example may be stored in the memory 202 and executable by the at least one processor 204 to perform various functions/operations as described herein according to various embodiments of the present invention.

5 [0029] In various embodiments, the system 200 for image processing corresponds to the method 100 of image stitching as described hereinbefore with reference to FIG. 1 according to various embodiments, therefore, various functions or operations configured to be performed by the least one processor 204 may correspond to various steps or operations of the method 100 of image stitching as described hereinbefore according to various embodiments, and thus need not be repeated with respect to the system 200 for image stitching for clarity and conciseness. In
10 other words, various embodiments described herein in context of the methods are analogously valid for the corresponding systems, and vice versa.

[0030] For example, in various embodiments, the memory 202 may have stored therein the first stitched image generating module 206, the guidance vector field generating module 208 and/or second stitched image generating module 210, which respectively correspond to various
15 steps (or operations or functions) of the method 100 of image stitching as described herein according to various embodiments, which are executable by the at least one processor 204 to perform the corresponding functions or operations as described herein.

[0031] A computing system, a controller, a microcontroller or any other system providing a processing capability may be provided according to various embodiments in the present
20 disclosure. Such a system may be taken to include one or more processors and one or more computer-readable storage mediums. For example, the system 200 for image stitching described hereinbefore may include a processor (or controller) 204 and a computer-readable storage medium (or memory) 202 which are for example used in various processing carried out therein as described herein. A memory or computer-readable storage medium used in various
25 embodiments may be a volatile memory, for example a DRAM (Dynamic Random Access Memory) or a non-volatile memory, for example a PROM (Programmable Read Only Memory), an EPROM (Erasable PROM), EEPROM (Electrically Erasable PROM), or a flash memory, e.g., a floating gate memory, a charge trapping memory, an MRAM (Magnetoresistive Random Access Memory) or a PCRAM (Phase Change Random Access Memory).

30 [0032] In various embodiments, a “circuit” may be understood as any kind of a logic implementing entity, which may be special purpose circuitry or a processor executing software stored in a memory, firmware, or any combination thereof. Thus, in an embodiment, a “circuit” may be a hard-wired logic circuit or a programmable logic circuit such as a programmable

processor, e.g., a microprocessor (e.g., a Complex Instruction Set Computer (CISC) processor or a Reduced Instruction Set Computer (RISC) processor). A “circuit” may also be a processor executing software, e.g., any kind of computer program, e.g., a computer program using a virtual machine code, e.g., Java. Any other kind of implementation of the respective functions
5 may also be understood as a “circuit” in accordance with various embodiments. Similarly, a “module” may be a portion of a system according to various embodiments and may encompass a “circuit” as described above, or may be understood to be any kind of a logic-implementing entity.

[0033] Some portions of the present disclosure are explicitly or implicitly presented in
10 terms of algorithms and functional or symbolic representations of operations on data within a computer memory. These algorithmic descriptions and functional or symbolic representations are the means used by those skilled in the data processing arts to convey most effectively the substance of their work to others skilled in the art. An algorithm is here, and generally, conceived to be a self-consistent sequence of steps leading to a desired result. The steps are
15 those requiring physical manipulations of physical quantities, such as electrical, magnetic or optical signals capable of being stored, transferred, combined, compared, and otherwise manipulated.

[0034] Unless specifically stated otherwise, and as apparent from the following, it will be appreciated that throughout the present specification, description or discussions utilizing terms
20 such as “generating”, “solving”, “converting”, “adjusting”, “determining” or the like, refer to the actions and processes of a computer system, or similar electronic device, that manipulates and transforms data represented as physical quantities within the computer system into other data similarly represented as physical quantities within the computer system or other information storage, transmission or display devices.

[0035] The present specification also discloses a system (e.g., which may also be embodied as a device or an apparatus), such as the system 200 for image stitching, for performing various operations/functions of various methods described herein. Such a system may be specially constructed for the required purposes, or may comprise a general purpose computer or other device selectively activated or reconfigured by a computer program stored in the computer. The
25 algorithms presented herein are not inherently related to any particular computer or other apparatus. Various general-purpose machines may be used with computer programs in accordance with the teachings herein. Alternatively, the construction of more specialized apparatus to perform various method steps may be appropriate.

[0036] In addition, the present specification also at least implicitly discloses a computer program or software/functional module, in that it would be apparent to the person skilled in the art that individual steps of various methods described herein may be put into effect by computer code. The computer program is not intended to be limited to any particular programming language and implementation thereof. It will be appreciated that a variety of programming languages and coding thereof may be used to implement the teachings of the disclosure contained herein. Moreover, the computer program is not intended to be limited to any particular control flow. There are many other variants of the computer program, which can use different control flows without departing from the scope of the invention. It will be appreciated by a person skilled in the art that various modules described herein (e.g., the first stitched image generating module 206, the guidance vector field generating module 208 and/or second stitched image generating module 210) may be software module(s) realized by computer program(s) or set(s) of instructions executable by a computer processor to perform the required functions, or may be hardware module(s) being functional hardware unit(s) designed to perform the required functions. It will also be appreciated that a combination of hardware and software modules may be implemented.

[0037] Furthermore, one or more of the steps of a computer program/module or method described herein may be performed in parallel rather than sequentially. Such a computer program may be stored on any computer readable medium. The computer readable medium may include storage devices such as magnetic or optical disks, memory chips, or other storage devices suitable for interfacing with a general purpose computer. The computer program when loaded and executed on such a general-purpose computer effectively results in an apparatus that implements the steps of the methods described herein.

[0038] In various embodiments, there is provided a computer program product, embodied in one or more computer-readable storage mediums (non-transitory computer-readable storage medium(s)), comprising instructions (e.g., the first stitched image generating module 206, the guidance vector field generating module 208 and/or second stitched image generating module 210) executable by one or more computer processors to perform the method 100 of image stitching as described herein with reference to FIG. 1 according to various embodiments. Accordingly, various computer programs or modules described herein may be stored in a computer program product receivable by a system therein, such as the system 200 for image stitching as shown in FIG. 2, for execution by at least one processor 204 of the system 200 to perform various functions.

[0039] In various embodiments, there is provided a computer program product, embodied in one or more computer-readable storage mediums (non-transitory computer-readable storage medium(s)), comprising instructions executable by one or more computer processors to perform the above-mentioned method 100 of image stitching according to various embodiments.

5 Accordingly, various computer programs or modules described herein may be stored in a computer program product receivable by a system therein, such as the above-mentioned system 200 for image stitching, for execution by at least one processor of the system to perform various functions.

[0040] Software or functional modules described herein may also be implemented as
10 hardware modules. More particularly, in the hardware sense, a module is a functional hardware unit designed for use with other components or modules. For example, a module may be implemented using discrete electronic components, or it can form a portion of an entire electronic circuit such as an Application Specific Integrated Circuit (ASIC). Numerous other possibilities exist. Those skilled in the art will appreciate that the software or functional
15 module(s) described herein can also be implemented as a combination of hardware and software modules.

[0041] In various embodiments, the system 200 for image stitching may be realized by any computer system (e.g., desktop or portable computer system) including at least one processor and a memory, such as a computer system 300 as schematically shown in FIG. 3 as an example
20 only and without limitation. Various methods/steps or functional modules may be implemented as software, such as a computer program being executed within the computer system 300, and instructing the computer system 300 (in particular, one or more processors therein) to conduct various functions or operations as described herein according to various embodiments. The computer system 300 may comprise a computer module 302, input modules, such as a keyboard
25 and/or a touchscreen 304 and a mouse 306, and a plurality of output devices such as a display 308, and a printer 310. The computer module 302 may be connected to a computer network 312 via a suitable transceiver device 314, to enable access to e.g., the Internet or other network systems such as Local Area Network (LAN) or Wide Area Network (WAN). The computer module 302 in the example may include a processor 318 for executing various instructions, a
30 Random Access Memory (RAM) 320 and a Read Only Memory (ROM) 322. The computer module 302 may also include a number of Input/Output (I/O) interfaces, for example I/O interface 324 to the display 308, and I/O interface 326 to the keyboard 304. The components of

the computer module 302 typically communicate via an interconnected bus 328 and in a manner known to the person skilled in the relevant art.

[0042] It will be appreciated by a person skilled in the art that the terminology used herein is for the purpose of describing various embodiments only and is not intended to be limiting of the present invention. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0043] Any reference to an element or a feature herein using a designation such as "first", "second" and so forth does not limit the quantity or order of such elements or features, unless stated or the context requires otherwise. For example, such designations may be used herein as a convenient way of distinguishing between two or more elements or instances of an element. Thus, a reference to first and second elements does not necessarily mean that only two elements can be employed, or that the first element must precede the second element. In addition, a phrase referring to "at least one of" a list of items refers to any single item therein or any combination of two or more items therein.

[0044] In order that the present invention may be readily understood and put into practical effect, various example embodiments of the present invention will be described hereinafter by way of examples only and not limitations. It will be appreciated by a person skilled in the art that the present invention may, however, be embodied in various different forms or configurations and should not be construed as limited to the example embodiments set forth hereinafter. Rather, these example embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the present invention to those skilled in the art.

[0045] According to various example embodiments, a hybrid image stitching method (or algorithm) (which may herein be simply referred to as the present method, e.g., corresponding to the method 100 of image stitching as described hereinbefore according to various embodiments) is provided for stitching all of the input images in both the image domain and the gradient domain. In various example embodiments, the hybrid image stitching method may include an optimization problem (e.g., a quadratic optimization problem) (e.g., corresponding to the "first optimization problem" as described hereinbefore according to various

embodiments), and a fast method may be provided for solving the quadratic optimization problem. In this regard, the hybrid image stitching method is advantageously simple and, for example, is suitable for performing panoramic imaging on mobile devices. As will be discussed later below, experimental results demonstrate that color transitions in the final stitched image at regions corresponding to transitions between adjacent images (or neighbouring images) are smooth without visible seams and the color tone of the final stitched image is accurate and natural (or realistic) compared to the input images (or base images). Accordingly, various example embodiments advantageously provide a fast method for image stitching to produce a natural stitched image.

10 [0046] In the hybrid image stitching method, according to various example embodiments of the present invention, all of the input images may be aligned using various conventional techniques or approaches known in the art, such as but not limited to those approaches described in Shum *et al.*, “Construction of panoramic mosaics with global and local alignment”, *International Journal of Computer Vision*, vol. 36, no. 3, pages 101-130, February 2000 and
15 Brown *et al.*, “Recognising panoramas”, in *Proceedings of the IEEE conference on computer vision and pattern recognition*, pages 1218-1225, 2003, and thus need not be described herein in detail for clarity and conciseness. The hybrid image stitching method may be referred to as hybrid (or being a hybrid approach) because all of the input images are blended in both the image domain and the gradient domain, or more particularly, the above-mentioned optimization
20 problem involves both the image and gradient domains to be solved to obtain the final stitched image.

[0047] In various example embodiments, an initial stitched image (e.g., corresponding to the “first stitched image” as described hereinbefore according to various embodiments) may be generated in the image domain based on a plurality of input images (which may be referred to
25 as an image domain stitching process (or method or algorithm)). Prior to the image domain stitching process, all of the input images may be corrected based on a color correction process (or method or algorithm) configured to minimize a global error function, so as to obtain a plurality of correction parameters (e.g., optimal correction coefficients, such as optimal gamma correction parameters) for the plurality of input images (e.g., for the whole image sequence),
30 respectively, simultaneously. In various example embodiments, after obtaining the corrected input images, instead of using the color blending (e.g., as described in Xiong *et al.*, “Color matching for high-quality panoramic images on mobile phones”, *IEEE Transactions Consumer Electronics*, vol. 56, no. 4, pages 2592-2600, November 2010 (herein referred to as the Xiong

reference) and Yao *et al.*, “Instant color matching for mobile panorama imaging”, *IEEE Signal Processing Letters*, vol. 22, no. 1, pages 6-10, January 2015 (herein referred to as the Yao reference)) to blend all the corrected input images, alpha blending (e.g., as described in Uyttendaele *et al.*, “Eliminating ghosting and exposure artifacts in image mosaics”, in *Proceedings of IEEE Conference on Computer Vision and Pattern Recognition*, vol. 1, pages 509-516, USA, October 2001 (herein referred to as the Uyttendaele reference), the content of which being hereby incorporated by reference in its entirety for all purposes) is adopted to blend all the corrected input images. Following the alpha blending of the corrected input images in the image domain, the initial stitched image is generated in the image domain. For example, such an image domain stitching process is simpler than the processes described in the above-mentioned Xiong and Yao references.

[0048] Various example embodiments note that, in the initial stitched image generated, there may be visible color tones change from one region (or area) to another region of the initial stitched image if the illumination and color differences among the input images are large. In this regard, although gradient domain stitching process (e.g., described in Zomet *et al.*, “Seamless image stitching by minimizing false edges”, *IEEE Transactions on Image Processing*, vol. 15, no. 4, pages 969-977, April 2006 (herein referred to as the Zomet reference) and Perez *et al.*, “Poisson image editing”, *ACM Transactions on Graphics*, vol. 22, no. 3, pages 313-318, July 2003 (herein referred to as the Perez reference)) is a different approach or direction compared to image domain stitching process, various example embodiments advantageously integrates the image domain stitching process and the gradient domain stitching process in a particular manner by forming a hybrid optimization problem (i.e., the above-mentioned optimization problem involving both the image and gradient domains simultaneously) (e.g., corresponding to the first optimization problem as described hereinbefore according to various embodiments) such that the input images are effectively and advantageously stitched in both the image and gradient domains. Such a hybrid approach has been advantageously found to additionally remove the visible color tones change in the initial stitched image, thereby, generating a more accurate and natural (or realistic) final stitched image that is without visible seams and without visible color tones change from one region to another region of the final stitched image.

[0049] In various example embodiments, the hybrid optimization problem (e.g., a quadratic optimization problem) may be configured as a cost function (e.g., a quadratic cost function) comprising two terms, namely, an image domain function and a gradient domain function. A

first term (the image domain function) may be configured to provide a measure of fidelity (e.g., closeness) of the final stitched image to the initial stitched image. A second term (the gradient domain function) may be configured to provide a measure of the fidelity (e.g., closeness) of fidelity of the gradient field of the final stitched image to the guidance vector field (e.g., generated by blending the gradient fields of all of the input images (respectively) via the alpha blending). Various example embodiments note that the second term dominates the quadratic cost function.

[0050] In various example embodiments, a separating (or decomposition) process or method is provided for solving the hybrid optimization problem. For example, the speed of the separating method has been found to be significantly faster than the conventional gradient domain approaches in the above-mentioned Zomet and Perez references, as well as faster than the conventional image domain approaches in the above-mentioned Xiong and Yao references.

[0051] In various example embodiments, the hybrid image stitching method may be applied to various visual applications such as panoramic imaging and detecting deepfake images/videos. In various example embodiments, the hybrid image stitching method may be improved by using intensity mapping functions (IMFs) amongst the input images to be stitched. For example, IMFs may also be applied to detect deepfake videos from the lighting condition point of view. As will be discussed later below, experimental results demonstrates that the stitched images (e.g., final stitched images) generated by the hybrid image stitching method according to various example embodiments of the present invention are better than conventional image stitching approaches, such as the conventional image domain stitching approaches described in the above-mentioned Xiong and Yao references.

HYBRID IMAGE STITCHING

[0052] The hybrid image stitching method (or algorithm) will now be described in further detail according to various example embodiments of the present invention.

[0053] In various example embodiments, a fast hybrid image stitching method is provided by introducing a hybrid optimization framework (corresponding the above-mentioned hybrid optimization problem). An input to the hybrid image stitching method (or algorithm) may be N (≥ 2) input images to be stitched, which may be denoted as Z_l ($1 \leq l \leq N$). An output of the hybrid image stitching method may be a final stitched image $\hat{Z}$ generated from the input images. In various example embodiments, all of the input images may be (or assumed to be) geometrically aligned. In various example embodiments, the hybrid image stitching method

may involve three key components. A first component is the initial stitched image $\tilde{Z}$ that is produced by an image domain stitching (or blending) process (or algorithm). A second component is the guidance vector field V that is generated by a gradient domain stitching (or blending) process (or algorithm). A third component is a hybrid optimization problem (or framework).

Generation of the Initial Stitched Image $\tilde{Z}$

[0054] In various example embodiments, the initial stitched image $\tilde{Z}$ may be generated by stitching N aligned input images Z_l ($1 \leq l \leq N$) in the image domain. As illumination changes across the scene, various example embodiments adjust the color and luminance of the input images prior to stitching such that differences between adjacent images can be minimized or removed and artifacts along the stitching seam can be minimized or removed. In various example embodiments, two different processes or methods are provided to generate the initial stitched image $\tilde{Z}$ in the image domain. A first image domain stitching process for generating the initial stitched image according to various example embodiments will now be described.

[0055] In the first image domain stitching process, all of the input images may first be converted from RGB color space to YUV color space, and the luminance components of the input images (whole input sequence) may be corrected via gamma correction parameters (e.g., corresponding to the “correction parameters” as described hereinbefore according to various embodiments). In various example embodiments, optimal gamma correction parameters may be obtained by matching, for each pair of adjacent input images (immediately adjacent input images) amongst the plurality of input images (all of the input images) having an overlapping region therebetween, the luminance components of the pair of adjacent input images in the overlapping region thereof in log domain. In various example embodiments, let γ_l be the gamma correction coefficient for input image Z_l , the cost function E_c may be defined as:

$$E_c = \sum_{l=2}^N (\gamma_{l-1} B_{l-1}^l - \gamma_l B_l^{l-1})^2 + \sum_{l=1}^N \lambda_{c,l} (1 - \gamma_l)^2 \quad (\text{Equation 1})$$

where $\lambda_{c,l}$ ($1 \leq l \leq N$) denote constants (e.g., empirically chosen). B_{l-1}^l and B_l^{l-1} denote the means of the gamma corrected luminance values in the overlapping region between the image Z_{l-1} and the image Z_l in log domain, which may be computed as:

$$\begin{cases} B_{l-1}^l = \log \left(\frac{1}{n_{l-1}^l} \sum_{p \in \Omega_{l-1}^l} (Y_{l-1}(p))^{\hat{\gamma}} \right) \\ B_l^{l-1} = \log \left(\frac{1}{n_{l-1}^l} \sum_{p \in \Omega_{l-1}^l} (Y_l(p))^{\hat{\gamma}} \right) \end{cases}$$

(Equation 2)

where Ω_{l-1}^l denotes the overlapping region between the image Z_{l-1} and the image Z_l . n_{l-1}^l denotes the number of pixels in the overlapping region Ω_{l-1}^l . $Y_{l-1}(p)$ and $Y_l(p)$ denote luminance value of pixel $p (= (i, j))$ in the images Z_{l-1} and Z_l , respectively. In various embodiments, to improve the matching of the luminance components of pair of adjacent input images, the luminance values used in calculating B_{l-1}^l and B_l^{l-1} in Equation (2) may first be linearized by raising the value to the power of $\hat{\gamma}$ ($\hat{\gamma} = 2.2$).

[0056] Accordingly, E_c is a quadratic objective function (or quadratic cost function) of γ_l 's. In various example embodiments, the corresponding optimization problem (e.g., corresponding to the “second optimization problem” as described hereinbefore according to various embodiments) may be solved in a closed form by setting the derivatives (of the function in Equation (1) with respect to γ_l) to zero. For example, when $\lambda_{c,1}$ is much larger than all other $\lambda_{c,l}$'s, an example sub-optimal solution may be given as:

$$\begin{cases} \gamma_1 = 1 \\ \gamma_2 = \frac{B_1^2}{B_2^1} \\ \gamma_l = \frac{\gamma_{l-1} [(B_{l-1}^l)^2 + \lambda_{c,l-1}]^{-\lambda_{c,l-1}}}{B_l^{l-1} B_{l-1}^l}, l > 2 \end{cases}$$

(Equation 3)

[0057] This is equivalent to choosing the first image as the reference one. In various example embodiments, after obtaining the optimal values of γ_l^* ($1 \leq l \leq N$), the luminance component of the l^{th} input image may be corrected to obtain the corresponding corrected input image based the following gamma correction:

$$\tilde{Y}_l(p) \leftarrow (Y_l(p))^{\gamma_l^*}.$$

(Equation 4)

[0058] In various example embodiments, based on tone mapping of high dynamic range images, linear correction is performed for all of the input images (RGB images) as:

$$\{R_l(p), G_l(p), B_l(p)\} \leftarrow \frac{\tilde{Y}_l(p)}{Y_l(p)} \{R_l(p), G_l(p), B_l(p)\}$$

(Equation 5)

[0059] The initial stitched image $\tilde{Z}$ may then obtained by stitching or merging all the corrected input images (e.g., color corrected input images) in image domain. According to various example embodiments, for a pixel p in the overlapping area of two adjacent input images, its new pixel value $\tilde{Z}(p)$ (i.e., the pixel value of the pixel p of the initial stitched image) may be calculated by linear blending according to a weighted combination of the corresponding pixels on the two adjacent input images (respectively). In various example embodiments, the weighting factor may be calculated based on the relative distance of the pixel p to the boundary of overlapping region between the two adjacent input images as:

$$w_{l-1}^l(p) = \frac{c_{l-1}^l + d - i}{2d}, \quad C_{l-1}^l - d \leq i \leq C_{l-1}^l + d$$

(Equation 6)

where C_{l-1}^l is the center of the overlap region Ω_{l-1}^l , and d is a tunable parameter controlling the width of the transition area.

[0060] Let τ_l be the region viewed exclusively in the image Z_l (i.e., the non-overlapping area in the image Z_l). In various example embodiments, the initial image $\tilde{Z}_l(p)$ may be determined or computed as:

$$\begin{cases} Z_l(p), & \text{if } p \in \tau_l \\ Z_l(p) + w_{l-1}^l(p)(Z_{l-1}(p) - Z_l(p)), & \text{if } p \in \Omega_{l-1}^l \\ Z_{l+1}(p) + w_l^{l+1}(p)(Z_l(p) - Z_{l+1}(p)), & \text{if } p \in \Omega_l^{l+1} \end{cases}$$

(Equation 7)

[0061] Accordingly, the first image domain stitching process for generating the initial stitched image according to various example embodiments is much simpler than the conventional image domain stitching algorithms described in the above-mentioned Xiong and Yao references.

[0062] A second image domain stitching process for generating the initial stitched image according to various example embodiments will now be described. The second image domain stitching process is based on the ghost removal process or algorithm as described in Li *et al.*, “Selectively detail-enhanced fusion of differently exposed images with moving objects”, *IEEE Transactions on Image Processing*, vol. 23, no. 10, pages 4372-4382 October 2014 (herein referred to as the Li reference), the content of which being hereby incorporated by reference in its entirety for all purposes. In various example embodiments, two major components of the ghost removal process are detection of inconsistent pixels and correction of inconsistent pixels.

Intensity mapping functions (IMFs) between two differently exposed images are adopted to

correct all the inconsistent pixels by the ghost removal process in the Li reference. In this regard, various example embodiments apply IMFs to generate the initial stitched image $\tilde{Z}$. In various example embodiments, the IMFs may be estimated by using the overlapping area between two adjacent (or neighboring) images (immediately adjacent images). For better understanding, a pair of input images Z_1 and Z_2 is taken as an example to illustrate the estimation of the IMFs according to various example embodiments of the present invention. For example, two cases are considered as follows:

[0063] *Case 1:* Camera response functions (CRFs) of the input image Z_2 , $F_{2,c}$ ($c \in \{R, G, B\}$) are available. If the input images Z_1 and Z_2 are captured by the same camera, the IMFs can be computed by using their different exposed times. Otherwise, an exposure time Δt may be estimated for the camera of Z_2 to capture the overlapping region in the input image Z_1 . In various example embodiments, the Δt can be estimated via minimizing the following cost function:

$$\sum_{p \in \Omega_1^2} W(Z_{1,c}(p)) W(Z_{2,c}(p)) \left[\frac{F_{2,c}^{-1}(Z_{1,c}(p))}{\Delta t} - \frac{F_{2,c}^{-1}(Z_{2,c}(p))}{\Delta t_2} \right]^2$$

(Equation 8)

where Δt_2 is the exposure time of Z_2 , and $F_{2,c}^{-1}(\cdot)$ is the inverse function of $F_{2,c}(\cdot)$. The function $W(z)$ is defined as:

$$W(z) = \begin{cases} z; & \text{if } z < 128 \\ 256 - z; & \text{otherwise} \end{cases}$$

(Equation 9)

[0064] *Case 2:* The CRFs of the input image Z_2 are not available. The IMFs may be first estimated by using the histograms of input images Z_1 and Z_2 in the overlapping region Ω_1^2 , and then be smoothed.

[0065] For simplicity, the IMFs from the input image Z_2 to the input image Z_1 may be denoted as $A_{2,1,c}$. In this regard, there may be color distortions if the IMFs are directly applied to correct the brightness and color of input image Z_2 . For example, two cases are considered below.

[0066] *Case I:* The input image Z_2 is brighter than the input image Z_1 . Note that the IMFs are not reliable in the over-exposed regions of Z_2 . A fixed ratio is adopted to darken an over-exposed pixel $Z_2(p)$ as $\kappa(p)Z_2(p)$ with the $\kappa(p)$ being determined or computed as:

$$\arg \min_{\kappa} \sum_{c \in \{R, G, B\}} W(Z_{2,c}(p)) [\kappa Z_{2,c}(p) - A_{2,1,c}(Z_{2,c}(p))]^2.$$

(Equation 10)

[0067] *Case II:* The input image Z_2 is darker than the input image Z_1 . The IMFs are not reliable in the under-exposed regions of Z_2 . Similarly, the fixed ratio is adopted to brighten an under-exposed pixel $Z_2(p)$ as $\kappa(p)Z_2(p)$, whereby the $\kappa(p)$ may be determined or computed according to the above-mentioned Equation (10).

[0068] In various example embodiments, besides improving the image stitching, the IMFs may also be applied to detect deepfake videos from the lighting conditions point of view. For example, the optical flow between a pair of frames in a video may be estimated by using an existing algorithm known in the art, such as described in Teed *et al.*, “RAFT: recurrent all-pairs field transforms for optical flow”, arXiv:2003.12039v2, 22 July 2020. The correspondence among moving objects in the two frames will be built up. The IMFs may then be applied to check the paired objects from the lighting condition point of view. This illustrates that the ghost removal algorithm is applicable to the detection of deepfake videos. Alternatively, the optical flow may also be applied to check the paired objects from the motion point of view.

Generation of the Guidance Vector Field V

[0069] In various example embodiments, the guidance vector field V may be generated based on gradient fields of the input images and based on a gradient domain stitching process. By way of an example and without limitation, based on the gradient domain stitching process according to various example embodiments, alpha blending may be employed in the gradient domain to generate the guidance vector field V .

[0070] For pixel p in the overlapping area of two adjacent images (immediately adjacent images), in various example embodiments, the initial vector field $V^{(0)}(p)$ may be calculated by linear blending where a weighted combination of the corresponding vector fields on the two adjacent images are used. The weighting factor may be calculated based on the relative distance of the pixel to the boundary of overlapping area as:

$$w_{l-1}^l(p) = \frac{C_{l-1}^l + d - i}{2d}; \quad C_{l-1}^l - d \leq i \leq C_{l-1}^l + d$$

(Equation 11)

where C_{l-1}^l is the center of the overlap region Ω_{l-1}^l , and d is a tunable parameter controlling the width of the transition area.

[0071] The initial vector field $V^{(0)}(p)$ may then be determined or computed as:

$$\begin{cases} \nabla Z_l(p), & \text{if } p \in \tau_l \\ \nabla Z_l(p) + w_{l-1}^l(p)(\nabla Z_{l-1}(p) - \nabla Z_l(p)), & \text{if } p \in \Omega_{l-1}^l \\ \nabla Z_{l+1}(p) + w_l^{l+1}(p)(\nabla Z_l(p) - \nabla Z_{l+1}(p)), & \text{if } p \in \Omega_l^{l+1} \end{cases}$$

(Equation 12)

where $\nabla Z_l(p)$ denotes the gradient of the gradient field of the input image Z_l at pixel p , Ω_{l-1}^l denotes the overlapping region between input image Z_{l-1} and input image Z_l , and Ω_l^{l+1} denotes the overlapping region between input image Z_{l+1} and input image Z_l .

[0072] Due to the gamma correction as described hereinbefore with reference to Equation (4), various example embodiments note that there may be mismatch between the gradient field of the initial stitched image and the initial vector field $V^{(0)}(p)$. To address this, various example embodiments adjust or tune the initial vector field $V^{(0)}(p)$ based on the gamma correction coefficient γ_l . Since the gamma correction coefficient γ_l is estimated rather than being exact, the guidance vector field $V(p)$ (or adjusted or corrected guidance vector field) may be generated by using the following weighted average:

$$V(p) = \theta V^{(0)}(p) + (1 - \theta) \frac{128^{\gamma_l}}{128} V^{(0)}(p)$$

(Equation 13)

where $\theta \in [0, 1]$, and its value is 5/8 (e.g., empirically chosen) according to various example embodiments.

Hybrid Optimization Framework

[0073] According to various example embodiments, a hybrid optimization problem or framework (e.g., corresponding to the “first optimization problem” as described hereinbefore according to various embodiments) is provided for stitching all of the input images Z_l ($1 \leq l \leq N$) in both the image domain and the gradient domain. Inputs may be the initial image $\tilde{Z}$ and the guidance vector field V , such as determined in the manner as described hereinbefore according to various embodiments. Output may be the final stitched image $\hat{Z}$. In various example embodiments, the hybrid optimization problem or framework may be formulated as a quadratic optimization problem. In various example embodiments, a fast method may be provided to solve the hybrid optimization problem so as to obtain an optimal solution.

[0074] In various example embodiments, the cost function may comprise two terms, namely, an image domain function and a gradient domain function. A first term (the image domain function) may be defined in the image domain and may be configured to provide a

measure of fidelity (e.g., closeness) of the final stitched image to the initial stitched image. By way of an example only and without limitation, the image domain function may be defined as:

$$E_1(\hat{Z}, \tilde{Z}) = \sum_p \|\hat{Z}(p) - \tilde{Z}(p)\|^2, \quad (\text{Equation 14})$$

- 5 **[0075]** A second term (the gradient domain function) may be defined in the gradient domain and may be configured to provide a measure of the fidelity (e.g., closeness) of fidelity of the gradient field of the final stitched image to the guidance vector field. By way of an example only and without limitation, the gradient domain function may be defined as:

$$E_2(\hat{Z}, V) = \sum_p \|\nabla \hat{Z}(p) - V(p)\|^2, \quad (\text{Equation 15})$$

10 where $\nabla \hat{Z}(p)$ denotes the gradient field of the output image (final stitched image) $\hat{Z}$ at pixel p . Accordingly, the second term may specify the desired gradient field of the output image $\hat{Z}$.

[0076] In various example embodiments, the hybrid optimization problem may be formulated as follows:

$$15 \quad \min_{\hat{Z}} \{E_1(\hat{Z}, \tilde{Z}) + \lambda E_2(\hat{Z}, V)\} \quad (\text{Equation 16})$$

where λ is a positive number and as an example is selected as 4096^2 in this disclosure if not specified. Accordingly, the second term in the gradient domain dominates the cost function. Note that the hybrid optimization problem becomes a Poisson equation if λ is selected as ∞ .

- 20 **[0077]** According to various example embodiments, a fast method is provided to solve the above-mentioned hybrid optimization problem (Equation 16) by decomposing it into each spatial dimension (e.g., vertical direction and horizontal direction) and solving the matrix with a sequence of 1D fast solvers. The corresponding 1D cost function may be defined with a 1D horizontal input signal I^h and a 1D guidance vector field V^h along the x dimension

- 25 $(i = 0, \dots, w - 1)$. In various example embodiments, defining $\frac{d\hat{Z}^h(i)}{dx}$ as $(\hat{Z}^h(i + 1) - \hat{Z}^h(i - 1))/2$, the 1D horizontal cost function is given as:

$$\sum_{i=0}^{w-1} (\hat{Z}^h(i) - \tilde{Z}^h(i))^2 + \lambda \sum_{i=1}^{w-2} \left(\frac{d\hat{Z}^h(i)}{dx} - V^h(i) \right)^2 \quad (\text{Equation 17})$$

- [0078]** In various example embodiments, an optimal solution may be obtained by solving the following linear equation:

$$A * \hat{Z}^h = D, \quad (\text{Equation 18})$$

where the matrix A is given as:

$$\begin{bmatrix} b_0 & 0 & c_0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & b_1 & 0 & c_1 & 0 & 0 & \cdots & 0 \\ a_0 & 0 & b_2 & 0 & c_2 & 0 & \cdots & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots & \vdots \\ 0 & \cdots & a_{x-2} & 0 & b_x & 0 & c_x & 0 \\ \vdots & \vdots & \vdots & \ddots & \ddots & \ddots & \ddots & \ddots \\ 0 & \cdots & 0 & 0 & a_{w-4} & 0 & b_{w-2} & 0 \\ 0 & \cdots & 0 & 0 & 0 & a_{w-3} & 0 & b_{w-1} \end{bmatrix}$$

(Equation 19)

with the coefficients a_i , b_i , and c_i as:

$$\begin{cases} a_i = -\lambda, & 0 \leq i \leq w-3 \\ c_i = -\lambda, & 0 \leq i \leq w-3 \\ b_0 = b_1 = 4 + \lambda \\ b_{w-2} = b_{w-1} = 4 + \lambda \\ b_i = 4 + 2\lambda, & 2 \leq i \leq w-3 \end{cases}$$

(Equation 20)

w is the width of the image $\hat{Z}$, and the vectors $\hat{Z}^h$ and D are given as:

$$\begin{cases} \hat{Z}^h = [\hat{Z}^h(0) \ \hat{Z}^h(1) \ \hat{Z}^h(2) \ \cdots \ \hat{Z}^h(w-1)]^T \\ D = [d_0 \ d_1 \ d_2 \ \cdots \ d_{w-1}]^T \end{cases}$$

(Equation 21)

and the coefficients d_i ($0 \leq i \leq w-1$) are

$$\begin{cases} d_0 = 4\tilde{Z}^h(0) - 2\lambda V^h(1) \\ d_1 = 4\tilde{Z}^h(1) - 2\lambda V^h(2) \\ d_{w-2} = 4\tilde{Z}^h(w-2) - 2\lambda V^h(w-3) \\ d_{w-1} = 4\tilde{Z}^h(w-1) - 2\lambda V^h(w-2) \\ d_i = 4\tilde{Z}^h(i) - 2\lambda(V^h(i-1) - V^h(i+1)), & 2 \leq i \leq w-3 \end{cases}$$

(Equation 22)

[0079] In various example embodiments, for simplicity, define two matrices as:

$$B = \begin{bmatrix} \tilde{b}_0 & 0 & c_0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & \tilde{b}_1 & 0 & c_1 & 0 & 0 & \cdots & 0 \\ a_0 & 0 & \tilde{b}_2 & 0 & c_2 & 0 & \cdots & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots & \vdots \\ 0 & \cdots & a_{x-2} & 0 & \tilde{b}_x & 0 & c_x & 0 \\ \vdots & \vdots & \vdots & \ddots & \ddots & \ddots & \ddots & \ddots \\ 0 & \cdots & 0 & 0 & a_{w-4} & 0 & \tilde{b}_{w-2} & 0 \\ 0 & \cdots & 0 & 0 & 0 & a_{w-3} & 0 & \tilde{b}_{w-1} \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & \frac{c_0}{\tilde{b}_0} & 0 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 & \frac{c_1}{\tilde{b}_1} & 0 & 0 & \cdots & 0 \\ 0 & 0 & 1 & 0 & \frac{c_2}{\tilde{b}_2} & 0 & \cdots & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & 0 & 1 & 0 & \frac{c_x}{\tilde{b}_x} & 0 \\ \vdots & \vdots & \vdots & \ddots & \ddots & \ddots & \ddots & \ddots \\ 0 & \cdots & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & \cdots & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

where $\tilde{b}_i$ ($0 \leq i \leq w-1$) is

$$\begin{cases} \tilde{b}_0 = b_0 \\ \tilde{b}_1 = b_1 \\ \tilde{b}_i = b_i - \frac{a_i - 2c_i - 2}{\tilde{b}_{i-2}}, 0 \leq i \leq w-1 \end{cases}$$

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(Equation 23)

[0080] It can be verified that:

$$A = B * C$$

(Equation 24)

[0081] Therefore, the optimal solution may be given as:

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$$\hat{Z}^{h,*} = C^{-1} * B^{-1} * D$$

(Equation 25)

where C^{-1} and B^{-1} are the inverse matrices of C and B , respectively, which can be easily computed.

[0082] Accordingly, a fast (or simple) method (or fast separation method) is provided for solving the hybrid optimization problem (Equation 16). In various example embodiments, the 1D solver may be iteratively applied along the rows and the columns of the image twice with λ_k computed at the k th iteration as $\frac{4^{2-k}}{10} \lambda$.

[0083] If λ is selected as ∞ , the matrix B in the decomposition (Equation (24)) is singular. The optimal solution cannot be computed via the fast separation method (Equation 25). Therefore, the fast separation method for solving the hybrid optimization problem is much faster than the conventional Poisson equation described in the above-mentioned Perez reference. Accordingly, the resultant hybrid image stitching method (or algorithm) according to various example embodiments of the present invention is advantageously significantly faster than the conventional gradient domain stitching algorithm.

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[0084] Accordingly, in the hybrid image stitching method according to various example embodiments of the present invention, the initial stitched image $\tilde{Z}$ may first be produced based on the image domain stitching process (or algorithm) as described hereinbefore. In the initial stitched image, possible seams are found to be not readily visible. However, there may be possible brightness or color tones change in the initial stitched image. The guidance vector field V may then be generated based on the gradient domain stitching process (or algorithm, e.g., gradient domain alpha blending algorithm) as described hereinbefore. In this regard, the guidance vector field V advantageously removes possible visible color tones and brightness change from one region to another region (i.e., in different regions) in the initial stitched image $\tilde{Z}$. The final stitched image $\hat{Z}$ may then be obtained by using the fast solver to solve the hybrid optimization problem (Equation 16) as described hereinbefore.

EXPERIMENTAL RESULTS

[0085] Experimental results will now be discussed to demonstrate the effectiveness and efficiency of the hybrid image stitching method (or algorithm) according to various example embodiments of the present invention. In various experimental results, for comparison purposes, the hybrid image stitching method is compared with algorithms in the above-mentioned Xiong and Yao references.

[0086] One set of images is first tested to compare the present image domain approach (i.e., the image domain stitching process (or algorithm) as described hereinbefore) and the present hybrid image stitching approach (hybrid image stitching method (or algorithm)) according to various example embodiments. In particular, FIGs. 4A to 4C depict images for a comparison between the present image domain stitching method and the present hybrid image stitching method, whereby FIG. 4A depicts input images (or base or original images), FIG. 4B depicts the initial stitched image generated from the input images by the present image domain stitching algorithm, and FIG. 4C depicts a final stitched image generated from the input images by the present hybrid image stitching algorithm. It can be observed from FIG. 4B that the left side of the initial stitched image is darker than the right side (more evident in the original color version of this image). In this regard, the color tone is changed from one region to another region of the initial stitched image due to large exposure difference among the input images (e.g., FIG. 4A) to be stitched. This color tone change problem is overcome by the present hybrid image stitching method.

[0087] The present hybrid image stitching approach is then compared with two conventional color correction algorithms described in the above-mentioned Xiong and Yao references by testing two sets of input images to be stitched. In particular, FIGs. 5A to 5D depict images for a comparison between the present hybrid image stitching method and the two conventional image stitching algorithms in the case of the input images having similar exposure level, whereby FIG. 5A depicts input images, FIG. 5B depicts the stitched image generated from the conventional image stitching algorithm described in the above-mentioned Xiong reference (hereinafter referred to as conventional image stitching algorithm 1), FIG. 5C depicts the stitched image generated from the conventional image stitching algorithm described in the above-mentioned Yao reference (hereinafter referred to as conventional image stitching algorithm 2), and FIG. 5D depicts the stitched image (final stitched image) generated from the present hybrid image stitching algorithm. From FIGs. 5B to 5D, it can be seen that no seam is visible between any two (adjacent) input images in all panorama images if the set of input images to be stitched has almost the same exposure level. The colors of the panorama images generated by both the conventional image stitching algorithm 2 and the present hybrid image stitching algorithm are natural, while there is slight color distortion in the panorama images generated by the conventional image stitching algorithm 1.

[0088] However, a set of images to be stitched may have significantly different exposure level, for example, due to different focus points. In this regard, there would be visible seam artifacts and color tones change from one region to another region in the panorama images generated by the above-mentioned two conventional image stitching algorithms 1 and 2 if the input images to be stitched have different exposures as illustrated in FIGs. 6A to 6D (more evident in the original color version of these images). In particular, FIGs. 6A to 6D depict images for a comparison between the present hybrid image stitching method and the above-mentioned two conventional image stitching algorithms in the case of the input images having significantly different exposure level, whereby FIG. 6A depicts input images, FIG. 6B depicts the stitched image generated from the conventional image stitching algorithm 1, FIG. 6C depicts the stitched image generated from the conventional image stitching algorithm 2, and FIG. 6D depicts the stitched image (final stitched image) generated from the present hybrid image stitching algorithm. Color distortion is also introduced by the conventional image stitching algorithm 1. As illustrated in FIG. 6D, the stitched image generated from the present hybrid image stitching method does not have visible seam artifacts or color tones changes across the stitched image. Accordingly, in this comparative example, it is demonstrated that the present

hybrid image stitching method advantageously solve the above-mentioned problems (visible seam artifacts and color tones change) associated with the above-mentioned conventional image stitching algorithms.

[0089] Finally, one more set of input images was tested to further compare the conventional image stitching algorithm 2, the present image domain stitching algorithm and the present hybrid stitching algorithm. In particular, FIGs. 7A to 7D depict images for a comparison amongst the conventional image stitching algorithm 2, the present image domain stitching algorithm and the present hybrid image stitching algorithm, whereby FIG. 7A depicts input images, FIG. 7B depicts the stitched image generated from the conventional image stitching algorithm 2, FIG. 7C depicts the stitched image generated from the present image domain stitching algorithm, and FIG. 7D depicts the stitched image (final stitched image) generated from the present hybrid image stitching algorithm. As shown in FIG. 7B, the seam for the stitching is visible for the stitched image generated by the conventional image stitching algorithm 2 (more evident in the original color version of this image). Furthermore, as shown in FIGs. 7B and 7C, the white cloud at the right side of the stitched image generated by the conventional image stitching algorithm 2 and the present image domain stitching algorithm is over-exposed (more evident in the original color version of these images). As illustrated in FIG. 7D, the stitched image generated from the present hybrid image stitching method does not have visible seam artifacts or color tones changes across the stitched image. Accordingly, in this comparative example, it is demonstrated that the present hybrid image stitching method advantageously solve the above-mentioned problems associated with the above-mentioned conventional image stitching algorithm and the present image domain stitching algorithm.

[0090] In various example embodiments, the λ in Equation (16) is configured or set accordingly in the present hybrid image stitching algorithm. As another example, a value of 16 for λ was tested with the input images shown in FIG 4A. FIG. 8 depicts a stitched image generated by the present hybrid image stitching algorithm from the input images shown in FIG. 4A with the value of λ in Equation (16) set as 16. As shown in FIG. 8, there is visible brightness change in the final stitched image generated. In particular, the white cloud at the right side of the stitched image is over-exposed. Therefore, in various example embodiments, the λ in Equation (16) is configured or set accordingly in the present hybrid image stitching algorithm such that there is no visible brightness change or color tones change across the final stitched image.

[0091] In terms of speed for the Matlab (R2007b) implementation on DELL M6700, the running times of the present image domain stitching algorithm and the present hybrid image stitching algorithm, and the above-mentioned conventional image stitching algorithm 2 for three 640×640 input images in FIG. 4A are 6.72, 17.45 and 21.38 seconds, respectively. The resolution of images in other figures are almost the same. Accordingly, it is demonstrated that both the present image domain stitching algorithm and the present hybrid image stitching algorithm are significantly faster than conventional gradient domain image stitching algorithms.

[0092] It will be appreciated by a person skilled in the art that the present hybrid image stitching method (or algorithm) according to various example embodiments may be employed in a variety of visual applications, such as but not limited to panoramic imaging and object insertion. For example, face manipulations including face swapping requires blending one altered face with a background which results in a typical object insertion. Therefore, image stitching is also important and applicable in face manipulations. For example, face detection is also important for the generation and detection of deepfake images/videos. For example, the method described in Zhang *et al.*, “Joint face detection and alignment using multitask cascaded convolutional networks”, *IEEE Signal Processing Letters*, vol. 23, no. 10, October 2016 (hereinafter referred to as the Zhang reference), is widely used to detect the face in an image Z . However, the method in the Zhang reference needs to be improved if the image Z is captured in low-lighting conditions. In this regard, various example embodiments found that the concept of local binary pattern (LBP) can be applied to improve the method in the Zhang reference.

[0093] The LBPs of the image $Z(p)$ may be defined as:

$$S^j(p) = \begin{cases} 1, & \text{if } Z(j) < Z(p) \\ 0, & \text{otherwise} \end{cases}, \quad (\text{Equation 26})$$

where j is a neighboring pixel of p .

[0094] Each pixel has eight neighboring pixels. There are eight LBP coded sub-images. Usually, all the sub-images are fused into one image. However, the fusion of all the eight sub-images is an issue due to the difficulty on defining weights of the sub-images. In this regard, various example embodiments utilizes the concatenation operation in the convolutional neural network (CNN). Accordingly, all the eight sub-images may be concatenated directly by the CNN in the Zhang reference. Once the face regions are detected, they may be used to generate or detect a forged image/video. In this regard, the present hybrid image stitching method may be employed to generate a forged image/video which may then be applied to train a deepfake image/video detection algorithm.

[0095] Accordingly, various example embodiments advantageously provide a fast hybrid image stitching method (or algorithm) for stitching all of the input images in both the image domain and the gradient domain. For example, the fast hybrid image stitching method is suitable for panoramic imaging on mobile devices due to its simplicity. As discussed above, experimental results demonstrate that the color transitions between adjacent (or neighboring) images are smooth without visible seams and the color tone of the final stitched image is accurate and natural (or realistic) compared to the input images (or base images).

[0096] Accordingly, various example embodiments provide a method of stitching two or more images while minimising the visual seams through an efficient and reduced processing method of image blending and through the manipulation of computer color space. Various example embodiments also further seeks to reduce processing time and resources by using a closed-form solution, utilising a quadratic cost function.

[0097] Accordingly, various example embodiments provide a method of stitching two or more images together comprising: converting the input images from the Red-Green-Blue (RGB) color space to the YUV (Luminance and Chrominance) color space; matching the acquired luminance values of the images and correcting the input images in the log-domain; generating gamma correction coefficients for the input images to generate corrected input images; stitching all corrected input images together; segmenting the new stitched image, identifying regions of the new stitched image retained from the original images (non-overlapped); and blending the overlapping segments through interpolation of pixels, the degree of which is determined by weighting factors associated with the pixels. In various example embodiments, the method may further comprises tuning the guidance vector field using the gamma correction coefficients determined for the input images, and a quadratic cost function is utilised to solve the hybrid optimization problem to obtain the final stitched image.

[0098] While embodiments of the invention have been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

What is claimed is:

- 5 1. A method of image stitching using at least one processor, the method comprising:
generating a first stitched image based on a plurality of input images and based on an
image domain stitching process;
generating a guidance vector field based on a plurality of gradient fields of the plurality
of input images and based on a gradient domain stitching process; and
10 generating a second stitched image based on solving a first optimization problem based
on the first stitched image and the guidance vector field.
2. The method according to claim 1, wherein
the first optimization problem is configured as a cost function comprising an image
15 domain function and a gradient domain function,
the image domain function is defined in an image domain and based on the first stitched
image, and
the gradient domain function is defined in a gradient domain and based on the guidance
vector field.
- 20 3. The method according to claim 2, wherein
the image domain function is configured to provide a measure of fidelity between the
second stitched image and the first stitched image; and
the gradient domain function is configured to provide a measure of fidelity between a
25 gradient field of the second stitched image and the guidance vector field.
4. The method according to claim 3, wherein said solving the first optimization problem
comprises:
decomposing the cost function into a plurality of spatial dimensions associated with the
30 second stitched image to obtain a plurality of one-dimensional (1D) cost functions, respectively;
and
solving, for each of the plurality of 1D cost functions, the 1D cost function based on
solving a corresponding linear equation.

5. The method according to claim 2, further comprising geometrically aligning the plurality of input images to produce a plurality of aligned input images, wherein
said generating the first stitched image based on the plurality of input images is based
5 on the plurality of aligned input images, and
said generating the guidance vector field based on the plurality of gradient fields of the plurality of input images is based on a plurality of gradient fields of the plurality of aligned input images.
- 10 6. The method according to claim 2, further comprising:
converting the plurality of input images from Red, Green and Blue (RGB) color space to Luminance-Bandwidth-Chrominance (YUV) color space; and
adjusting, for each of the plurality of input images, a luminance component of the input image based on a correction parameter determined for the input image to produce a color
15 corrected input image so as to obtain a plurality of color corrected input images, wherein
said generating the first stitched image based on the plurality of input images is based on the plurality of corrected input images, and
said generating the guidance vector field based on the plurality of gradient fields of the plurality of input images is based on a plurality of gradient fields of the plurality of color
20 corrected input images.
7. The method according to claim 6, further comprising:
determining a plurality of correction parameters for the plurality of input images, respectively, based on solving a second optimization problem configured for matching, for each
25 pair of adjacent input images amongst the plurality of input images having an overlapping region therebetween, the luminance components of the pair of adjacent input images in the overlapping region thereof.
8. The method according to claim 6, wherein said generating the first stitched image
30 comprises:
for each pair of adjacent input images amongst the plurality of input images having an overlapping region therebetween, determining a pixel value of each pixel of the first stitched

image in the overlapping region based on a weighted combination of corresponding pixels of the pair of adjacent input images.

9. The method according to claim 6, wherein said generating the guidance vector field
5 comprises:

for each pair of adjacent input images amongst the plurality of input images having an overlapping region therebetween, determining a gradient at each pixel of the guidance vector field in the overlapping region based on a weighted combination of gradients at corresponding pixels of the pair of adjacent input images.

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10. The method according to claim 9, wherein said generating the guidance vector field further comprises adjusting the guidance vector field based on a plurality of correction parameters determined for the plurality of input images, respectively.

- 15 11. A system for image stitching, the system comprising:
a memory; and
at least one processor communicatively coupled to the memory and configured to:
generate a first stitched image based on a plurality of input images and based on an image domain stitching process;
20 generate a guidance vector field based on a plurality of gradient fields of the plurality of input images and based on a gradient domain stitching process; and
generate a second stitched image based on solving a first optimization problem based on the first stitched image and the guidance vector field.

- 25 12. The system according to claim 11, wherein
the first optimization problem is configured as a cost function comprising an image domain function and a gradient domain function,
the image domain function is defined in an image domain and based on the first stitched image, and
30 the gradient domain function is defined in a gradient domain and based on the guidance vector field.

13. The system according to claim 12, wherein

the image domain function is configured to provide a measure of fidelity between the second stitched image and the first stitched image; and

the gradient domain function is configured to provide a measure of fidelity between a gradient field of the second stitched image and the guidance vector field.

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14. The system according to claim 13, wherein said solving the first optimization problem comprises:

decomposing the cost function into a plurality of spatial dimensions associated with the second stitched image to obtain a plurality of one-dimensional (1D) cost functions, respectively;

10 and

solving, for each of the plurality of 1D cost functions, the 1D cost function based on solving a corresponding linear equation.

15. The system according to claim 12, wherein the at least one processor is further configured to:

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convert the plurality of input images from Red, Green and Blue (RGB) color space to Luminance-Bandwidth-Chrominance (YUV) color space; and

adjust, for each of the plurality of input images, a luminance component of the input image based on a correction parameter determined for the input image to produce a color corrected input image so as to obtain a plurality of color corrected input images, wherein

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said generate the first stitched image based on the plurality of input images is based on the plurality of color corrected input images, and

said generate the guidance vector field based on the plurality of gradient fields of the plurality of input images is based on a plurality of gradient fields of the plurality of color corrected input images.

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16. The system according to claim 15, wherein the at least one processor is further configured to:

determine a plurality of correction parameters for the plurality of input images, respectively, based on solving a second optimization problem configured for matching, for each pair of adjacent input images amongst the plurality of input images having an overlapping region therebetween, the luminance components of the pair of adjacent input images in the overlapping region thereof.

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17. The system according to claim 15, wherein said generating the first stitched image comprises:

5 for each pair of adjacent input images amongst the plurality of input images having an overlapping region therebetween, determining a pixel value of each pixel of the first stitched image in the overlapping region based on a weighted combination of corresponding pixels of the pair adjacent of input images.

18. The system according to claim 15, wherein said generate the guidance vector field
10 comprises:

for each pair of adjacent input images amongst the plurality of input images having an overlapping region therebetween, determining a gradient at each pixel of the guidance vector field in the overlapping region based on a weighted combination of gradients at corresponding pixels of the pair adjacent of input images.

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19. The system according to claim 18, wherein said generate the guidance vector field further comprises adjusting the guidance vector field based on a plurality of correction parameters determined for the plurality of input images, respectively.

20. A computer program product, embodied in one or more non-transitory computer-readable storage mediums, comprising instructions executable by at least one processor to perform a method of image stitching, the method comprising:

generating a first stitched image based on a plurality of input images and based on an image domain stitching process;

25 generating a guidance vector field based on a plurality of gradient fields of the plurality of input images and based on a gradient domain stitching process; and

generating a second stitched image based on solving a first optimization problem based on the first stitched image and the guidance vector field.

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