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Mirroring in image guided surgery

Abstract

An imaging system, including a head-mounted display worn by a system operator. A marker defines a plane when attached to a human subject. Optically reflective elements are disposed on the marker and on opposing sides of the plane in a non-symmetrical arrangement with respect to the plane. A memory stores a graphical representation of a tool used in a procedure performed on the human subject, and an image of anatomy of the human subject. A camera attached to the display acquires an image of the marker and the tool. A processor analyzes the image to identify the plane and to identify a side of the plane wherein the camera is located, and to render to the display the image of the anatomy of the human subject with the graphical representation of the tool superimposed thereon from a point of view in the identified side of the plane.

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9240046	12/2015	Carrell et al.	N/A	N/A

9244278	12/2015	Sugiyama et al.	N/A	N/A
9247240	12/2015	Park et al.	N/A	N/A
9259192	12/2015	Ishihara	N/A	N/A
9265572	12/2015	Fuchs et al.	N/A	N/A
9269192	12/2015	Kobayashi	N/A	N/A
9283052	12/2015	Rodriguez Ponce	N/A	N/A
9286730	12/2015	Bar-Zeev et al.	N/A	N/A
9289267	12/2015	Sauer et al.	N/A	N/A
9294222	12/2015	Proctor, Jr.	N/A	N/A
9300949	12/2015	Ahearn	N/A	N/A
9305354	12/2015	Burlon et al.	N/A	N/A
9310591	12/2015	Hua et al.	N/A	N/A
9320474	12/2015	Demri et al.	N/A	N/A
9323055	12/2015	Baillot	N/A	N/A
9330477	12/2015	Rappel	N/A	N/A
9335547	12/2015	Takano et al.	N/A	N/A
9335567	12/2015	Nakamura	N/A	N/A
9341704	12/2015	Picard et al.	N/A	N/A
9344686	12/2015	Moharir	N/A	N/A
9349066	12/2015	Koo et al.	N/A	N/A
9349520	12/2015	Demetriou et al.	N/A	N/A
9364294	12/2015	Razzaque et al.	N/A	N/A
9370332	12/2015	Paladini et al.	N/A	N/A
9373166	12/2015	Azar	N/A	N/A
9375639	12/2015	Kobayashi et al.	N/A	N/A
9378558	12/2015	Kajiwara et al.	N/A	N/A
9380287	12/2015	Nistico et al.	N/A	N/A
9387008	12/2015	Sarvestani et al.	N/A	N/A
9392129	12/2015	Simmons	N/A	N/A
9395542	12/2015	Tilleman et al.	N/A	N/A
9398936	12/2015	Razzaque et al.	N/A	N/A
9400384	12/2015	Griffith	N/A	N/A
9414041	12/2015	Ko et al.	N/A	N/A
9424611	12/2015	Kanjirathinkal et al.	N/A	N/A
9424641	12/2015	Wiemker et al.	N/A	N/A
9427286	12/2015	Siewerdsen et al.	N/A	N/A
9438894	12/2015	Park et al.	N/A	N/A
9443488	12/2015	Borenstein et al.	N/A	N/A
9453804	12/2015	Tahtali	N/A	N/A
9456878	12/2015	MacFarlane et al.	N/A	N/A
9465235	12/2015	Chang	N/A	N/A
9468373	12/2015	Larsen	N/A	N/A
9470908	12/2015	Frankel et al.	N/A	N/A
9473766	12/2015	Douglas et al.	N/A	N/A
9492222	12/2015	Singh	N/A	N/A
9495585	12/2015	Bicer et al.	N/A	N/A
9498132	12/2015	Maier-Hein et al.	N/A	N/A
9498231	12/2015	Haider et al.	N/A	N/A
9507155	12/2015	Morimoto	N/A	N/A
9513495	12/2015	Waters	N/A	N/A

9521966	12/2015	Schwartz	N/A	N/A
9526443	12/2015	Berme et al.	N/A	N/A
9530382	12/2015	Simmons	N/A	N/A
9532846	12/2016	Nakamura	N/A	N/A
9532849	12/2016	Anderson et al.	N/A	N/A
9533407	12/2016	Ragner	N/A	N/A
9538962	12/2016	Hannaford et al.	N/A	N/A
9545233	12/2016	Sirpad et al.	N/A	N/A
9546779	12/2016	Rementer	N/A	N/A
9547174	12/2016	Gao et al.	N/A	N/A
9547940	12/2016	Sun et al.	N/A	N/A
9557566	12/2016	Fujimaki	N/A	N/A
9560318	12/2016	Reina et al.	N/A	N/A
9561095	12/2016	Nguyen et al.	N/A	N/A
9561446	12/2016	Brecher	N/A	N/A
9565415	12/2016	Zhang et al.	N/A	N/A
9572661	12/2016	Robin et al.	N/A	N/A
9576398	12/2016	Zehner et al.	N/A	N/A
9576556	12/2016	Simmons	N/A	N/A
9581822	12/2016	Morimoto	N/A	N/A
9610056	12/2016	Lavallee et al.	N/A	N/A
9612657	12/2016	Bertram et al.	N/A	N/A
9626936	12/2016	Bell	N/A	N/A
9629595	12/2016	Walker et al.	N/A	N/A
9633431	12/2016	Merlet	N/A	N/A
9645395	12/2016	Bolas et al.	N/A	N/A
9646423	12/2016	Sun et al.	N/A	N/A
9672597	12/2016	Amiot et al.	N/A	N/A
9672607	12/2016	Demri et al.	N/A	N/A
9672640	12/2016	Kleiner	N/A	N/A
9675306	12/2016	Morton	N/A	N/A
9675319	12/2016	Razzaque et al.	N/A	N/A
9684980	12/2016	Royalty et al.	N/A	N/A
9690119	12/2016	Garofolo et al.	N/A	N/A
RE46463	12/2016	Fienbloom et al.	N/A	N/A
9693748	12/2016	Rai et al.	N/A	N/A
9710968	12/2016	Dillavou et al.	N/A	N/A
9713502	12/2016	Finkman et al.	N/A	N/A
9724119	12/2016	Hissong et al.	N/A	N/A
9724165	12/2016	Arata et al.	N/A	N/A
9726888	12/2016	Giartosio et al.	N/A	N/A
9728006	12/2016	Varga	N/A	N/A
9729831	12/2016	Birnkrant et al.	N/A	N/A
9746739	12/2016	Alton et al.	N/A	N/A
9757034	12/2016	Desjardins et al.	N/A	N/A
9757087	12/2016	Simon et al.	N/A	N/A
9766441	12/2016	Rappel	N/A	N/A
9766459	12/2016	Alton et al.	N/A	N/A
9767608	12/2016	Lee et al.	N/A	N/A
9770203	12/2016	Berme et al.	N/A	N/A

9772102	12/2016	Ferguson	N/A	N/A
9772495	12/2016	Tam et al.	N/A	N/A
9791138	12/2016	Feinbloom et al.	N/A	N/A
9800995	12/2016	Libin et al.	N/A	N/A
9805504	12/2016	Zhang et al.	N/A	N/A
9808148	12/2016	Miller et al.	N/A	N/A
9839448	12/2016	Reckling et al.	N/A	N/A
9844413	12/2016	Daon et al.	N/A	N/A
9851080	12/2016	Wilt et al.	N/A	N/A
9858663	12/2017	Penney et al.	N/A	N/A
9861446	12/2017	Lang	N/A	N/A
9864214	12/2017	Fass	N/A	N/A
9872733	12/2017	Shoham et al.	N/A	N/A
9875544	12/2017	Rai et al.	N/A	N/A
9877642	12/2017	Duret	N/A	N/A
9885465	12/2017	Nguyen	N/A	N/A
9886552	12/2017	Dillavou et al.	N/A	N/A
9886760	12/2017	Liu et al.	N/A	N/A
9892564	12/2017	Cvetko et al.	N/A	N/A
9898866	12/2017	Fuchs et al.	N/A	N/A
9901414	12/2017	Lively et al.	N/A	N/A
9911187	12/2017	Steinle et al.	N/A	N/A
9911236	12/2017	Bar et al.	N/A	N/A
9927611	12/2017	Rudy et al.	N/A	N/A
9928629	12/2017	Benishti et al.	N/A	N/A
9940750	12/2017	Dillavou et al.	N/A	N/A
9943374	12/2017	Merritt et al.	N/A	N/A
9947110	12/2017	Haimerl	N/A	N/A
9952664	12/2017	Border et al.	N/A	N/A
9956054	12/2017	Aguirre-Valencia	N/A	N/A
9958674	12/2017	Border	N/A	N/A
9959620	12/2017	Merlet	N/A	N/A
9959629	12/2017	Dillavou et al.	N/A	N/A
9965681	12/2017	Border et al.	N/A	N/A
9968297	12/2017	Connor	N/A	N/A
9980780	12/2017	Lang	N/A	N/A
9986228	12/2017	Woods	N/A	N/A
D824523	12/2017	Paoli et al.	N/A	N/A
10010379	12/2017	Gibby et al.	N/A	N/A
10013531	12/2017	Richards et al.	N/A	N/A
10015243	12/2017	Kazerani et al.	N/A	N/A
10016243	12/2017	Esterberg	N/A	N/A
10022064	12/2017	Kim et al.	N/A	N/A
10022065	12/2017	Ben-Yishai et al.	N/A	N/A
10022104	12/2017	Sell et al.	N/A	N/A
10023615	12/2017	Bonny	N/A	N/A
10026015	12/2017	Cavusoglu et al.	N/A	N/A
10034713	12/2017	Yang et al.	N/A	N/A
10042167	12/2017	McDowall et al.	N/A	N/A
10046165	12/2017	Frewin et al.	N/A	N/A

10055838	12/2017	Elenbaas et al.	N/A	N/A
10066816	12/2017	Chang	N/A	N/A
10067359	12/2017	Ushakov	N/A	N/A
10073515	12/2017	Awdeh	N/A	N/A
10080616	12/2017	Wilkinson et al.	N/A	N/A
10082680	12/2017	Chung	N/A	N/A
10085709	12/2017	Lavallee et al.	N/A	N/A
10105187	12/2017	Corndorf et al.	N/A	N/A
10107483	12/2017	Oren	N/A	N/A
10108833	12/2017	Hong et al.	N/A	N/A
10123840	12/2017	Dorman	N/A	N/A
10130378	12/2017	Bryan	N/A	N/A
10132483	12/2017	Feinbloom et al.	N/A	N/A
10134166	12/2017	Benishti et al.	N/A	N/A
10134194	12/2017	Kepner et al.	N/A	N/A
10139652	12/2017	Windham	N/A	N/A
10139920	12/2017	Isaacs et al.	N/A	N/A
10142496	12/2017	Rao et al.	N/A	N/A
10151928	12/2017	Ushakov	N/A	N/A
10154239	12/2017	Casas	N/A	N/A
10159530	12/2017	Ang	N/A	N/A
10163207	12/2017	Merlet	N/A	N/A
10166079	12/2018	McLachlin et al.	N/A	N/A
10175507	12/2018	Nakamura	N/A	N/A
10175753	12/2018	Boesen	N/A	N/A
10181361	12/2018	Dillavou et al.	N/A	N/A
10186055	12/2018	Takahashi et al.	N/A	N/A
10188672	12/2018	Wagner	N/A	N/A
10194131	12/2018	Casas	N/A	N/A
10194990	12/2018	Amanatullah et al.	N/A	N/A
10194993	12/2018	Roger et al.	N/A	N/A
10195076	12/2018	Fateh	N/A	N/A
10197803	12/2018	Badiali et al.	N/A	N/A
10197816	12/2018	Waisman et al.	N/A	N/A
10207315	12/2018	Appleby et al.	N/A	N/A
10212517	12/2018	Beltran et al.	N/A	N/A
10230719	12/2018	Vaughn et al.	N/A	N/A
10231893	12/2018	Lei et al.	N/A	N/A
10235606	12/2018	Miao et al.	N/A	N/A
10240769	12/2018	Braganca et al.	N/A	N/A
10247965	12/2018	Ton	N/A	N/A
10251724	12/2018	McLachlin et al.	N/A	N/A
10261324	12/2018	Chuang et al.	N/A	N/A
10262424	12/2018	Ketcha et al.	N/A	N/A
10274731	12/2018	Maimone	N/A	N/A
10278777	12/2018	Lang	N/A	N/A
10292768	12/2018	Lang	N/A	N/A
10296805	12/2018	Yang et al.	N/A	N/A
10319154	12/2018	Chakravarthula et al.	N/A	N/A
10326975	12/2018	Casas	N/A	N/A

10332267	12/2018	Rai et al.	N/A	N/A
10339719	12/2018	Jagga et al.	N/A	N/A
10352543	12/2018	Braganca et al.	N/A	N/A
10357146	12/2018	Fiebel et al.	N/A	N/A
10357574	12/2018	Hilderbrand et al.	N/A	N/A
10366489	12/2018	Boettger et al.	N/A	N/A
10368947	12/2018	Lang	N/A	N/A
10368948	12/2018	Tripathi	N/A	N/A
10382748	12/2018	Benishti et al.	N/A	N/A
10383654	12/2018	Yilmaz et al.	N/A	N/A
10386645	12/2018	Abou Shousha	N/A	N/A
10388076	12/2018	Bar-Zeev et al.	N/A	N/A
10398514	12/2018	Ryan et al.	N/A	N/A
10401657	12/2018	Jiang et al.	N/A	N/A
10405825	12/2018	Rai et al.	N/A	N/A
10405927	12/2018	Ang	N/A	N/A
10413752	12/2018	Berlinger et al.	N/A	N/A
10419655	12/2018	Sivan	N/A	N/A
10420626	12/2018	Tokuda et al.	N/A	N/A
10420813	12/2018	Newell-Rogers et al.	N/A	N/A
10424115	12/2018	Ellerbrock	N/A	N/A
D862469	12/2018	Sadot et al.	N/A	N/A
10426554	12/2018	Siewerdsen et al.	N/A	N/A
10429675	12/2018	Greget	N/A	N/A
10431008	12/2018	Djajadiningrat et al.	N/A	N/A
10433814	12/2018	Razzaque et al.	N/A	N/A
10434335	12/2018	Takahashi et al.	N/A	N/A
10441236	12/2018	Bar-Tal et al.	N/A	N/A
10444514	12/2018	Abou Shousha et al.	N/A	N/A
10447947	12/2018	Liu	N/A	N/A
10448003	12/2018	Grafenberg	N/A	N/A
10449040	12/2018	Lashinski et al.	N/A	N/A
10453187	12/2018	Peterson et al.	N/A	N/A
10463434	12/2018	Siegler et al.	N/A	N/A
10465892	12/2018	Feinbloom et al.	N/A	N/A
10466487	12/2018	Blum et al.	N/A	N/A
10470732	12/2018	Baumgart et al.	N/A	N/A
10473314	12/2018	Braganca et al.	N/A	N/A
10485989	12/2018	Jordan et al.	N/A	N/A
10488663	12/2018	Choi	N/A	N/A
D869772	12/2018	Gand	N/A	N/A
D870977	12/2018	Berggren et al.	N/A	N/A
10492755	12/2018	Lin et al.	N/A	N/A
10499997	12/2018	Weinstein et al.	N/A	N/A
10502363	12/2018	Edwards et al.	N/A	N/A
10504231	12/2018	Fiala	N/A	N/A
10507066	12/2018	Dimaio et al.	N/A	N/A
10511822	12/2018	Casas	N/A	N/A
10517544	12/2018	Taguchi et al.	N/A	N/A
10537395	12/2019	Perez	N/A	N/A

10540780	12/2019	Cousins et al.	N/A	N/A
10543485	12/2019	Ismagilov et al.	N/A	N/A
10546423	12/2019	Jones et al.	N/A	N/A
10548557	12/2019	Lim et al.	N/A	N/A
10555775	12/2019	Hoffman et al.	N/A	N/A
10568535	12/2019	Roberts et al.	N/A	N/A
10571696	12/2019	Urey et al.	N/A	N/A
10571716	12/2019	Chapiro	N/A	N/A
10573086	12/2019	Bar-Zeev et al.	N/A	N/A
10573087	12/2019	Gallop et al.	N/A	N/A
10577630	12/2019	Zhang et al.	N/A	N/A
10586400	12/2019	Douglas	N/A	N/A
10591737	12/2019	Yildiz et al.	N/A	N/A
10592748	12/2019	Cousins et al.	N/A	N/A
10594998	12/2019	Casas	N/A	N/A
10595716	12/2019	Nazareth et al.	N/A	N/A
10601950	12/2019	Devam et al.	N/A	N/A
10602114	12/2019	Casas	N/A	N/A
10603113	12/2019	Lang	N/A	N/A
10603133	12/2019	Wang et al.	N/A	N/A
10606085	12/2019	Toyama	N/A	N/A
10610172	12/2019	Hummel et al.	N/A	N/A
10610179	12/2019	Altmann	N/A	N/A
10613352	12/2019	Knoll	N/A	N/A
10617566	12/2019	Esmonde	N/A	N/A
10620460	12/2019	Carabin	N/A	N/A
10621738	12/2019	Miao et al.	N/A	N/A
10625099	12/2019	Takahashi et al.	N/A	N/A
10626473	12/2019	Mariani et al.	N/A	N/A
10631905	12/2019	Asfora et al.	N/A	N/A
10631907	12/2019	Zucker et al.	N/A	N/A
10634331	12/2019	Feinbloom et al.	N/A	N/A
10634921	12/2019	Blum et al.	N/A	N/A
10638080	12/2019	Ovchinnikov et al.	N/A	N/A
10646285	12/2019	Siemionow et al.	N/A	N/A
10650513	12/2019	Penney et al.	N/A	N/A
10650594	12/2019	Jones et al.	N/A	N/A
10652525	12/2019	Woods	N/A	N/A
10653495	12/2019	Gregerson et al.	N/A	N/A
10660715	12/2019	Dozeman	N/A	N/A
10663738	12/2019	Carlvik et al.	N/A	N/A
10665033	12/2019	Bar-Zeev et al.	N/A	N/A
10670937	12/2019	Alton et al.	N/A	N/A
10672145	12/2019	Albiol et al.	N/A	N/A
10682112	12/2019	Pizaine et al.	N/A	N/A
10682767	12/2019	Grafenberg et al.	N/A	N/A
10687901	12/2019	Thomas	N/A	N/A
10691397	12/2019	Clements	N/A	N/A
10702713	12/2019	Mori et al.	N/A	N/A
10706540	12/2019	Merlet	N/A	N/A

10709398	12/2019	Schweizer	N/A	N/A
10713801	12/2019	Jordan et al.	N/A	N/A
10716643	12/2019	Justin et al.	N/A	N/A
10722733	12/2019	Takahashi	N/A	N/A
10725535	12/2019	Yu	N/A	N/A
10731832	12/2019	Koo	N/A	N/A
10732721	12/2019	Clements	N/A	N/A
10742949	12/2019	Casas	N/A	N/A
10743939	12/2019	Lang	N/A	N/A
10743943	12/2019	Razeto et al.	N/A	N/A
10747315	12/2019	Tungare et al.	N/A	N/A
10748319	12/2019	Tao et al.	N/A	N/A
10758315	12/2019	Johnson et al.	N/A	N/A
10777094	12/2019	Rao et al.	N/A	N/A
10777315	12/2019	Zehavi et al.	N/A	N/A
10781482	12/2019	Gubatayao et al.	N/A	N/A
10792110	12/2019	Leung et al.	N/A	N/A
10799145	12/2019	West et al.	N/A	N/A
10799296	12/2019	Ang	N/A	N/A
10799298	12/2019	Crawford et al.	N/A	N/A
10799316	12/2019	Sela et al.	N/A	N/A
10810799	12/2019	Tepper et al.	N/A	N/A
10818019	12/2019	Piat et al.	N/A	N/A
10818101	12/2019	Gallop et al.	N/A	N/A
10818199	12/2019	Buras et al.	N/A	N/A
10825563	12/2019	Gibby et al.	N/A	N/A
10827164	12/2019	Perreault et al.	N/A	N/A
10831943	12/2019	Santarone et al.	N/A	N/A
10835296	12/2019	Elimelech et al.	N/A	N/A
10838206	12/2019	Fortin-Deschnes et al.	N/A	N/A
10839629	12/2019	Jones et al.	N/A	N/A
10839956	12/2019	Beydoun et al.	N/A	N/A
10841556	12/2019	Casas	N/A	N/A
10842002	12/2019	Chang	N/A	N/A
10842461	12/2019	Johnson et al.	N/A	N/A
10849691	12/2019	Zucker et al.	N/A	N/A
10849693	12/2019	Lang	N/A	N/A
10849710	12/2019	Liu	N/A	N/A
10861236	12/2019	Geri et al.	N/A	N/A
10865220	12/2019	Ebetino et al.	N/A	N/A
10869517	12/2019	Halpern	N/A	N/A
10869727	12/2019	Yanof et al.	N/A	N/A
10872472	12/2019	Watola et al.	N/A	N/A
10877262	12/2019	Luxembourg	N/A	N/A
10877296	12/2019	Lindsey et al.	N/A	N/A
10878639	12/2019	Douglas et al.	N/A	N/A
10893260	12/2020	Trail et al.	N/A	N/A
10895742	12/2020	Schneider et al.	N/A	N/A
10895743	12/2020	Dausmann	N/A	N/A
10895906	12/2020	West et al.	N/A	N/A

10898151	12/2020	Harding et al.	N/A	N/A
10908420	12/2020	Lee et al.	N/A	N/A
10921595	12/2020	Rakshit et al.	N/A	N/A
10921613	12/2020	Gupta et al.	N/A	N/A
10928321	12/2020	Rawle	N/A	N/A
10928638	12/2020	Ninan et al.	N/A	N/A
10929670	12/2020	Troy et al.	N/A	N/A
10935815	12/2020	Castaeda	N/A	N/A
10935816	12/2020	Ban et al.	N/A	N/A
10936537	12/2020	Huston	N/A	N/A
10939973	12/2020	Dimaio et al.	N/A	N/A
10939977	12/2020	Messinger et al.	N/A	N/A
10941933	12/2020	Ferguson	N/A	N/A
10946108	12/2020	Zhang et al.	N/A	N/A
10950338	12/2020	Douglas	N/A	N/A
10951872	12/2020	Casas	N/A	N/A
10964095	12/2020	Douglas	N/A	N/A
10964124	12/2020	Douglas	N/A	N/A
10966768	12/2020	Poulos	N/A	N/A
10969587	12/2020	McDowall et al.	N/A	N/A
10993754	12/2020	Kuntz et al.	N/A	N/A
11000335	12/2020	Dorman	N/A	N/A
11002994	12/2020	Jiang et al.	N/A	N/A
11006093	12/2020	Hegyi	N/A	N/A
11013550	12/2020	Rioux et al.	N/A	N/A
11013560	12/2020	Lang	N/A	N/A
11013562	12/2020	Marti et al.	N/A	N/A
11013573	12/2020	Chang	N/A	N/A
11013900	12/2020	Malek et al.	N/A	N/A
11016302	12/2020	Freeman et al.	N/A	N/A
11019988	12/2020	Fiebel et al.	N/A	N/A
11027027	12/2020	Manning et al.	N/A	N/A
11029147	12/2020	Abovitz et al.	N/A	N/A
11030809	12/2020	Wang	N/A	N/A
11041173	12/2020	Zhang et al.	N/A	N/A
11045663	12/2020	Mori et al.	N/A	N/A
11049293	12/2020	Chae et al.	N/A	N/A
11049476	12/2020	Fuchs et al.	N/A	N/A
11050990	12/2020	Casas	N/A	N/A
11057505	12/2020	Dharmatilleke	N/A	N/A
11058390	12/2020	Douglas	N/A	N/A
11061257	12/2020	Hakim	N/A	N/A
11064904	12/2020	Kay et al.	N/A	N/A
11065062	12/2020	Frushour et al.	N/A	N/A
11067387	12/2020	Marell et al.	N/A	N/A
11071497	12/2020	Hallack et al.	N/A	N/A
11079596	12/2020	Hua et al.	N/A	N/A
11087039	12/2020	Duff et al.	N/A	N/A
11090019	12/2020	Siemionow et al.	N/A	N/A
11097129	12/2020	Sakata et al.	N/A	N/A

11099376	12/2020	Steier et al.	N/A	N/A
11103320	12/2020	Leboeuf et al.	N/A	N/A
D930162	12/2020	Cremer et al.	N/A	N/A
11109762	12/2020	Steier et al.	N/A	N/A
11112611	12/2020	Kessler et al.	N/A	N/A
11122164	12/2020	Gigante	N/A	N/A
11123604	12/2020	Fung	N/A	N/A
11129562	12/2020	Roberts et al.	N/A	N/A
11132055	12/2020	Jones et al.	N/A	N/A
11135015	12/2020	Crawford et al.	N/A	N/A
11135016	12/2020	Frielinghaus et al.	N/A	N/A
11137610	12/2020	Kessler et al.	N/A	N/A
11141221	12/2020	Hobeika et al.	N/A	N/A
11153549	12/2020	Casas	N/A	N/A
11153555	12/2020	Healy et al.	N/A	N/A
11163176	12/2020	Karafin et al.	N/A	N/A
11164324	12/2020	Liu et al.	N/A	N/A
11166006	12/2020	Hegyi	N/A	N/A
11169380	12/2020	Manly et al.	N/A	N/A
11172990	12/2020	Lang	N/A	N/A
11179136	12/2020	Kohli et al.	N/A	N/A
11180557	12/2020	Noelle	N/A	N/A
11181747	12/2020	Kessler et al.	N/A	N/A
11185891	12/2020	Cousins et al.	N/A	N/A
11187907	12/2020	Osterman et al.	N/A	N/A
11202682	12/2020	Staunton et al.	N/A	N/A
11207150	12/2020	Healy et al.	N/A	N/A
11217028	12/2021	Jones et al.	N/A	N/A
11224483	12/2021	Steinberg et al.	N/A	N/A
11224763	12/2021	Takahashi et al.	N/A	N/A
11227417	12/2021	Berlinger et al.	N/A	N/A
11231787	12/2021	Isaacs et al.	N/A	N/A
11243404	12/2021	McDowall et al.	N/A	N/A
11244508	12/2021	Kazanzides et al.	N/A	N/A
11253216	12/2021	Crawford et al.	N/A	N/A
11253323	12/2021	Hughes et al.	N/A	N/A
11257190	12/2021	Mao et al.	N/A	N/A
11257241	12/2021	Tao	N/A	N/A
11263772	12/2021	Siemionow et al.	N/A	N/A
11269401	12/2021	West et al.	N/A	N/A
11272151	12/2021	Casas	N/A	N/A
11278359	12/2021	Siemionow et al.	N/A	N/A
11278413	12/2021	Lang	N/A	N/A
11280480	12/2021	Wilt et al.	N/A	N/A
11284846	12/2021	Graumann et al.	N/A	N/A
11291521	12/2021	Im	N/A	N/A
11294167	12/2021	Ishimoda	N/A	N/A
11297285	12/2021	Pierce	N/A	N/A
11300252	12/2021	Nguyen	N/A	N/A
11300790	12/2021	Cheng et al.	N/A	N/A

11304621	12/2021	Merschon et al.	N/A	N/A
11304759	12/2021	Kovtun et al.	N/A	N/A
11307402	12/2021	Steier et al.	N/A	N/A
11308663	12/2021	Alhrishy et al.	N/A	N/A
11311341	12/2021	Lang	N/A	N/A
11317973	12/2021	Calloway et al.	N/A	N/A
11337763	12/2021	Choi	N/A	N/A
11348257	12/2021	Lang	N/A	N/A
11350072	12/2021	Quiles Casas	N/A	N/A
11350965	12/2021	Yilmaz et al.	N/A	N/A
11351006	12/2021	Aferzon et al.	N/A	N/A
11354813	12/2021	Piat et al.	N/A	N/A
11360315	12/2021	Tu et al.	N/A	N/A
11373342	12/2021	Stafford et al.	N/A	N/A
11382699	12/2021	Wassall et al.	N/A	N/A
11382700	12/2021	Calloway et al.	N/A	N/A
11382712	12/2021	Elimelech et al.	N/A	N/A
11382713	12/2021	Healy et al.	N/A	N/A
11389252	12/2021	Gera et al.	N/A	N/A
11393229	12/2021	Zhou et al.	N/A	N/A
11399895	12/2021	Soper et al.	N/A	N/A
11402524	12/2021	Song et al.	N/A	N/A
11406338	12/2021	Tolkowsky	N/A	N/A
11412202	12/2021	Hegyi	N/A	N/A
11423554	12/2021	Borsdorf et al.	N/A	N/A
11430203	12/2021	Navab et al.	N/A	N/A
11432828	12/2021	Lang	N/A	N/A
11432931	12/2021	Lang	N/A	N/A
11443428	12/2021	Petersen et al.	N/A	N/A
11443431	12/2021	Flossmann et al.	N/A	N/A
11452568	12/2021	Lang	N/A	N/A
11452570	12/2021	Tolkowsky	N/A	N/A
11460915	12/2021	Frielinghaus et al.	N/A	N/A
11461936	12/2021	Freeman et al.	N/A	N/A
11461983	12/2021	Jones et al.	N/A	N/A
11464580	12/2021	Kemp et al.	N/A	N/A
11464581	12/2021	Calloway	N/A	N/A
11475625	12/2021	Douglas	N/A	N/A
11478214	12/2021	Siewerdsen et al.	N/A	N/A
11483532	12/2021	Quiles Casas	N/A	N/A
11488021	12/2021	Sun et al.	N/A	N/A
11490986	12/2021	Ben-Yishai	N/A	N/A
11510750	12/2021	Dulin et al.	N/A	N/A
11513358	12/2021	McDowall et al.	N/A	N/A
11527002	12/2021	Govari	N/A	N/A
11528393	12/2021	Garofolo et al.	N/A	N/A
11544031	12/2022	Harviainen	N/A	N/A
11573420	12/2022	Sarma et al.	N/A	N/A
11589927	12/2022	Oezbek et al.	N/A	N/A
11627924	12/2022	Alexandroni et al.	N/A	N/A

11644675	12/2022	Manly et al.	N/A	N/A
11648016	12/2022	Hathaway et al.	N/A	N/A
11651499	12/2022	Wang et al.	N/A	N/A
11657518	12/2022	Ketcha et al.	N/A	N/A
11666458	12/2022	Kim et al.	N/A	N/A
11669984	12/2022	Siewerdsen et al.	N/A	N/A
11686947	12/2022	Loyola et al.	N/A	N/A
11699236	12/2022	Avital et al.	N/A	N/A
11712582	12/2022	Miyazaki et al.	N/A	N/A
11715210	12/2022	Haslam et al.	N/A	N/A
11719941	12/2022	Russell	N/A	N/A
11730389	12/2022	Farshad et al.	N/A	N/A
11733516	12/2022	Edwin et al.	N/A	N/A
11734901	12/2022	Jones et al.	N/A	N/A
11744657	12/2022	Leboeuf et al.	N/A	N/A
11750794	12/2022	Benishti et al.	N/A	N/A
11766296	12/2022	Wolf et al.	N/A	N/A
11798178	12/2022	Merlet	N/A	N/A
11801097	12/2022	Crawford et al.	N/A	N/A
11801115	12/2022	Elimelech et al.	N/A	N/A
11808943	12/2022	Robaina et al.	N/A	N/A
11815683	12/2022	Sears et al.	N/A	N/A
11826111	12/2022	Mahfouz	N/A	N/A
11832886	12/2022	Dorman	N/A	N/A
11838493	12/2022	Healy et al.	N/A	N/A
11839433	12/2022	Schaewe et al.	N/A	N/A
11839501	12/2022	Takahashi et al.	N/A	N/A
11864934	12/2023	Junio et al.	N/A	N/A
11885752	12/2023	St-Aubin et al.	N/A	N/A
11892647	12/2023	Hung et al.	N/A	N/A
11896445	12/2023	Gera et al.	N/A	N/A
11900620	12/2023	Lalys et al.	N/A	N/A
11914155	12/2023	Zhu et al.	N/A	N/A
11918310	12/2023	Roh et al.	N/A	N/A
11922631	12/2023	Haslam et al.	N/A	N/A
11941814	12/2023	Crawford et al.	N/A	N/A
11944508	12/2023	Cowin et al.	N/A	N/A
11948265	12/2023	Gibby et al.	N/A	N/A
11950968	12/2023	Wiggermann	N/A	N/A
11957420	12/2023	Lang	N/A	N/A
11961193	12/2023	Pelzl et al.	N/A	N/A
11963723	12/2023	Vilsmeier et al.	N/A	N/A
11972582	12/2023	Yan et al.	N/A	N/A
11974819	12/2023	Finley et al.	N/A	N/A
11974887	12/2023	Elimelech et al.	N/A	N/A
11977232	12/2023	Wu et al.	N/A	N/A
11980429	12/2023	Wolf et al.	N/A	N/A
11980506	12/2023	Wolf et al.	N/A	N/A
11980507	12/2023	Elimelech et al.	N/A	N/A
11980508	12/2023	Elimelech et al.	N/A	N/A

11983824	12/2023	Avisar et al.	N/A	N/A
12002171	12/2023	Jones et al.	N/A	N/A
12010285	12/2023	Quiles Casas	N/A	N/A
12014497	12/2023	Hong et al.	N/A	N/A
12019314	12/2023	Steines et al.	N/A	N/A
12026897	12/2023	Frantz et al.	N/A	N/A
12033322	12/2023	Laaksonen et al.	N/A	N/A
12044856	12/2023	Gera et al.	N/A	N/A
12044858	12/2023	Gera et al.	N/A	N/A
12053247	12/2023	Chiou	N/A	G06F 3/011
12056830	12/2023	Cvetko et al.	N/A	N/A
12059281	12/2023	Weingarten et al.	N/A	N/A
12063338	12/2023	Quiles Casas	N/A	N/A
12063345	12/2023	Benishti et al.	N/A	N/A
12069233	12/2023	Benishti et al.	N/A	N/A
12076158	12/2023	Geiger et al.	N/A	N/A
12076196	12/2023	Elimelech et al.	N/A	N/A
12079385	12/2023	Ben-Yishai et al.	N/A	N/A
12112483	12/2023	Grady et al.	N/A	N/A
12114933	12/2023	Seo et al.	N/A	N/A
12115028	12/2023	Dulin et al.	N/A	N/A
12127800	12/2023	Qian et al.	N/A	N/A
12133772	12/2023	Calloway et al.	N/A	N/A
12136176	12/2023	Spaas et al.	N/A	N/A
12142365	12/2023	Kaethner et al.	N/A	N/A
12150821	12/2023	Gera et al.	N/A	N/A
12178666	12/2023	Wolf et al.	N/A	N/A
12186028	12/2024	Gera et al.	N/A	N/A
12201384	12/2024	Wolf et al.	N/A	N/A
12206837	12/2024	Benishti et al.	N/A	N/A
12239385	12/2024	Wolf et al.	N/A	N/A
2002/0082498	12/2001	Wendt et al.	N/A	N/A
2003/0059097	12/2002	Abovitz et al.	N/A	N/A
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2003/0156144	12/2002	Morita	N/A	N/A
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2007/0273610	12/2006	Baillot	N/A	N/A
2008/0002809	12/2007	Bodduluri	N/A	N/A
2008/0007645	12/2007	McCutchen	N/A	N/A
2008/0035266	12/2007	Danziger	N/A	N/A
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2008/0183065	12/2007	Goldbach	N/A	N/A
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2009/0300540	12/2008	Russell	N/A	N/A
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2012/0143050	12/2011	Heigl	N/A	N/A
2012/0155064	12/2011	Waters	N/A	N/A
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2013/0234935	12/2012	Griffith	N/A	N/A
2013/0237811	12/2012	Mihailescu et al.	N/A	N/A
2013/0245461	12/2012	Maier-Hein et al.	N/A	N/A
2013/0249787	12/2012	Morimoto	N/A	N/A
2013/0249945	12/2012	Kobayashi	N/A	N/A
2013/0265623	12/2012	Sugiyama et al.	N/A	N/A
2013/0267838	12/2012	Fronk et al.	N/A	N/A
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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION (1) This application is a continuation of U.S. patent application Ser. No. 17/827,710, filed May 29, 2022, which is a continuation of U.S. patent application Ser. No. 16/724,297, filed Dec. 22, 2019 (now U.S. Pat. No. 11,382,712), each of which is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION
(1) This invention relates generally to an augmented reality system, and specifically to correct image projection when it is used in image guided surgery.
BACKGROUND
(2) Correct imaging is important in image guided surgery, and a number of systems are known in the art for producing correct imaging.

(3) U.S. Pat. Nos. 7,630,753 and 9,757,087, to Simon et al., describe a surgical instrument navigation system that allows a surgeon to invert the three-dimensional perspective of the instrument to match their perspective of the actual instrument.
(4) U.S. Pat. No. 9,538,962, to Hannaford et al., describes a system for providing networked communications. The system includes a plurality of head-mountable devices, each in communication with a control system via a communication network.
(5) U.S. Pat. No. 9,710,968, to Dillavou et al., describes a system for role designation with multiple sources.
(6) U.S. Pat. No. 9,886,552, to Dillavou et al., describes a method for image registration that includes rendering a common field of interest that reflects a presence of a plurality of elements. At least one of the elements is a remote element located remotely from another of the elements.
(7) U.S. Pat. No. 9,940,750, to Dillavou et al., describes a method for role negotiation that can comprise rendering a common field of interest that reflects a presence of a plurality of elements. At least one of the elements is a remote element located remotely from another of the elements.
(8) U.S. Pat. No. 9,959,629, to Dillavou et al., describes a method for managing spatiotemporal uncertainty in image processing. The method can comprise determining motion from a first image to a second image.
(9) U.S. Pat. No. 10,194,131, to Casas, describes a real-time surgery method for displaying a stereoscopic augmented view of a patient from a static or dynamic viewpoint of the surgeon. The method employs real-time three-dimensional surface reconstruction for preoperative and intraoperative image registration.
(10) US Patent Application 2011/0216060, to Weising et al., describes a method for controlling a view of a virtual scene with a portable device. A signal is received and the portable device is synchronized to make the location of the portable device a reference point in a three-dimensional (3D) space.
(11) US Patent Application 2017/0027650, to Merck et al., describes receiving data characterizing a mother video feed acquired by an endoscopic video capture device. The mother video feed can be for characterizing an operative field within a patient.
(12) US Patent Application 2017/0251900, to Hansen et al., describes a depiction system for generating a real time correlated depiction of movements of a surgical tool for uses in minimally invasive surgery.
(13) US Patent Application 2017/0367771, to Tako et al., describes a virtual reality surgical navigation method that includes a step of receiving data indicative of a surgeon's current head position, including a direction of view and angle of view of the surgeon.
(14) US Patent Application 2018/0247128, to Alvi et al., describes a system for accessing a surgical dataset including surgical data collected during performance of a surgical procedure. The surgical data can include video data of the surgical procedure.
(15) Documents incorporated by reference in the present patent application are to be considered an integral part of the application except that, to the extent that any terms are defined in these incorporated documents in a manner that conflicts with definitions made explicitly or implicitly in the present specification, only the definitions in the present specification should be considered.

SUMMARY

(16) An embodiment of the present invention provides an imaging system, consisting of: a head-mounted display configured to be worn by an operator of the system; a marker configured to be attached to a human subject and defining a plane when attached to the human subject, the marker having optically reflective elements disposed on the marker and on opposing sides of the plane in a non-symmetrical arrangement with respect to the plane; a memory configured to store a graphical representation of a tool used in a procedure performed by the operator on the human subject, and an image of anatomy of the human subject; a camera attached to the display and configured to acquire an input image of the marker and of the tool; and a processor configured to analyze the input image

so as to identify the plane and to identify a side of the plane wherein the camera is located, and to render to the display the image of the anatomy of the human subject with the graphical representation of the tool superimposed thereon from a point of view in the identified side of the plane.

(17) In a disclosed embodiment the plane makes an angle between +20° and −20° with a sagittal plane of the human subject. Alternatively, the plane makes an angle between +20° and −20° with an axial plane of the human subject.

(18) In a further disclosed embodiment the marker has a two-dimensional surface which makes an angle between +20° and −20° with a frontal plane of the human subject.

(19) In a yet further disclosed embodiment the marker defines a further plane and the optically reflective elements are disposed on opposing sides of the further plane in a non-symmetrical arrangement with respect to the further plane, and the processor is configured to analyze the input image so as to identify the further plane and to identify a side of the further plane wherein the camera is located, and to render to the display the image of the anatomy of the human subject with the graphical representation of the tool superimposed thereon from a point of view in the identified side of the further plane. Typically, the plane and the further plane are orthogonal to each other.

(20) In an alternative embodiment the camera is located at a vertical height above the marker, and the processor is configured: to ascertain the vertical height in response to the acquired input image of the marker; to calculate a pair of planes, each of the pair having a preset acute angle to the identified plane and defining a first acute-angled wedge region and a second acute-angled wedge region to the identified plane; and when the display moves so that the point of view crosses the first acute-angled wedge region and the second acute-angled wedge region, or begins within the first acute-angled wedge region and crosses the second acute-angled wedge region, while the camera remains at the vertical height, to render to the display the image of the anatomy of the human subject with the graphical representation of the tool superimposed thereon from the point of view of a region opposite the identified side.

(21) Typically the preset acute angle is less than or equal to 10°.

(22) In a further alternative embodiment the camera is located at a vertical height above the marker, and the processor is configured: to ascertain the vertical height in response to the acquired input image of the marker; and when the display moves so that the vertical height changes, to render unchanged to the display the image of the anatomy of the human subject with the graphical representation of the tool superimposed thereon.

(23) There is further provided, according to an embodiment of the present invention, an imaging system, consisting of: a first head-mounted display configured to be worn by a first operator of the system; a second head-mounted display configured to be worn by a second operator of the system; a marker configured to be attached to a human subject and defining a plane when attached to the human subject, the marker having optically reflective elements disposed on the marker and on opposing sides of the plane in a non-symmetrical arrangement with respect to the plane; a memory configured to store a graphical representation of a tool used in a procedure performed by the first operator on the human subject, and an image of anatomy of the human subject; a first camera attached to the first display and configured to acquire a first input image of the marker and of the tool; a second camera attached to the second display and configured to acquire a second input image of the marker and of the tool; and a processor configured to: analyze the first input image so as to identify the plane and to identify a first side of the plane wherein the first camera is located, and to render to the first display the image of the anatomy of the human subject with the graphical representation of the tool superimposed thereon from a first point of view in the identified first side of the plane, and analyze the second input image so as to identify the plane and to identify a second side of the plane wherein the second camera is located, and to render to the second display the image of the anatomy of the human subject with the graphical representation of the tool superimposed thereon from a second point of view in the identified second side of the plane.

(24) There is further provided, according to an embodiment of the present invention, a method, consisting of: providing a head-mounted display configured to be worn by an operator of an imaging system; attaching a marker to a human subject, the marker defining a plane when attached, the marker having optically reflective elements disposed on the marker and on opposing sides of the plane in a non-symmetrical arrangement with respect to the plane; storing in a memory a graphical representation of a tool used in a procedure performed by the operator on the human subject, and storing an image of anatomy of the human subject in the memory; attaching a camera to the display; acquiring an input image of the marker and of the tool with the camera; and analyzing the input image so as to identify the plane and to identify a side of the plane wherein the camera is located, and to render to the display the image of the anatomy of the human subject with the graphical representation of the tool superimposed thereon from a point of view in the identified side of the plane.
(25) The present disclosure will be more fully understood from the following detailed description of the embodiments thereof, taken together with the drawings. A brief description of the drawings follows.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIG. **1** is a schematic illustration of an initial preparatory stage of a medical procedure, according to an embodiment of the present invention;
(2) FIGS. **2**, **3**, and **4** are schematic depictions of entities used in the initial stage, according to an embodiment of the present invention;
(3) FIG. **5** is a flowchart of steps performed to register a patient marker with the anatomy of a patient during the initial preparatory stage;
(4) FIG. **6** is a schematic illustration of a subsequent stage of the procedure, according to an embodiment of the present invention;
(5) FIG. **7** is a flowchart of steps performed during the subsequent stage, according to an embodiment of the present invention;
(6) FIG. **8** shows schematic figures illustrating images generated in the subsequent stage, according to an embodiment of the present invention;
(7) FIG. **9** is a schematic top-down view of a surface of a marker used in the procedure; and
(8) FIG. **10** is a schematic illustration of the subsequent stage of the procedure when there are two operators for the procedure, according to an embodiment of the present invention.
DETAILED DESCRIPTION OF EMBODIMENTS
Overview
(9) A head-mounted display, for a medical procedure that implements an imaging system, such as an augmented reality system, in the display, typically needs to access stored computerized tomography (CT) files of the anatomy of a human subject. The display is worn by an operator of the system, and the accessed files are presented to the operator as scanned planes of the subject in the display. However, for the presentation to be correctly oriented, it is necessary to know the position of the operator with respect to the subject.
(10) Embodiments of the present invention provide an imaging system that determines the operator position automatically, and so displays an image of the patient anatomy, and of a tool used in the procedure, automatically.
(11) In addition to a head-mounted display (HMD) that is worn by an operator of the system, the system comprises a marker that is attached to the human subject. The marker defines a plane of asymmetry when attached to the human subject, since the marker has optically reflective elements disposed on the marker and on opposing sides of the plane in a non-symmetrical arrangement with

respect to the plane. The plane of asymmetry is typically approximately parallel to one of the main anatomical planes of the human subject.

(12) In the imaging system a memory stores a graphical representation of a tool used in the procedure performed by the operator, and the memory also stores an image of the anatomy of the human subject. A camera is attached to the HMD, and acquires an input image of the marker and of the tool. A processor analyzes the input image so as to identify the plane and to identify a side of the plane wherein the camera is located. The processor then renders to the display the image of the anatomy of the human subject with the graphical representation of the tool superimposed thereon from a point of view in the identified side of the plane.

DETAILED DESCRIPTION

(13) In the following, all directional references (e.g., upper, lower, upward, downward, left, right, top, bottom, above, below, vertical, and horizontal) are only used for identification purposes to aid the reader's understanding of the present invention, and do not create limitations, particularly as to the position, orientation, or use of embodiments of the invention.

(14) In the description, like elements in the drawings are identified by like numerals, and like elements are differentiated as necessary by appending a letter to the identifying numeral.

(15) Reference is now made to FIGS. **1**, **2**, **3**, and **4**, which are diagrams according to an embodiment of the present invention. FIG. **1** is a schematic illustration of an initial preparatory stage of a medical procedure using an imaging system **20**, and FIGS. **2**, **3**, and **4** are schematic depictions of entities used in the initial stage. The medical procedure exemplified here is performed on the back of a human subject **22**, herein also termed patient **22**, and during the initial stage of the procedure an operator **26** of system also herein termed medical professional **26** makes an incision **24** into the patient's back. The professional inserts a spinous process clamp **30** into the incision, so that opposing jaws of the clamp are located on opposite sides of the spinous processes. The professional then slides the clamp over the vertebral laminas, and adjusts the clamp to grip one or more spinous processes, selected by the professional, of the patient. Clamp **30** is described below with reference to FIG. **4**, and a clamp such as clamp **30** is described in more detail in U.S. Patent Application 2019/0175228 which is incorporated herein by reference.

(16) Clamp **30** acts as a support for a patient marker **38**, which is attached rigidly to the clamp. During substantially all of the procedure, i.e., during the initial, as well as the subsequent stages, patient marker **38** is used as a fiducial for patient **30**, since because of its rigid connection to the patient, any movement of the patient is reflected in a corresponding motion of the patient marker. In order to operate as such a fiducial, in embodiments of the present invention, in the initial stage of the procedure marker **38** is registered with the anatomy of patient **30**, herein assumed to comprise the skeleton of the patient, as is described herein.

(17) During the procedure medical professional **26** wears a head-mounted display (HMD) **64** which is configured to present stored images, that are aligned with patient **22**, to professional **26**. HMD **64** is described further below.

(18) As is also described below, in serving as a fiducial, marker **38** performs two functions: a first function wherein the marker is used to maintain registration between frames of reference of the head-mounted display and the patient's anatomy, and a second function wherein the marker is used to ascertain where the medical professional is located with respect to the patient. Thus, for the second function, the marker provides a location of the medical professional as being on a left side or a right side of the patient, or on an upper side or a lower side of the patient.

(19) An augmented reality head-mounted display such as HMD **64** is described in more detail in U.S. Patent Application 2017/0178375 which is incorporated herein by reference.

(20) During the initial stage of the procedure, a registration marker **40** is placed on the patient's back, and is used to implement the registration of patient marker **38** with the anatomy of patient **30**. In contrast to patient marker **38**, registration marker **40** is typically only used during the initial stage of the procedure, i.e., for the registration of the patient marker **38**, and once the registration

has been performed, for the subsequent procedure stages the registration marker may be removed from the patient's back. As will be apparent from the following description, only registration marker **40** is subject to fluoroscopy, and patient marker **38** is not subject to fluoroscopy.
(21) Also during the initial stage of the procedure, a camera **42**, fixedly attached to head-mounted display **64**, is used to image the registration marker and the patient marker. Camera **42** typically operates in the visible and/or near-visible spectrum, i.e., at wavelengths of approximately 300 nm-900 nm.
(22) A processing system **28** is coupled, by cables and/or wirelessly, to camera **42**. System **28** comprises a computer processor **32**, a memory **33** comprising stored images **35** that include images **304**, **308**, and **324**, described below, a screen **34**, and an input device **36** such as a pointing device. The system is configured to analyze the images acquired by the camera, as is described further below. Other functions of system **28** are also described below.
(23) In order to operate, HMD **64** is coupled to processor **32** of system **28**, or alternatively HMD **64** has its own dedicated processor which performs similar functions to those performed by processor **32**. When HMD **64** is operative it presents stored images, that are aligned with patient **22**, to professional **26**.
(24) FIGS. **2** and **3** are respectively schematic perspective and cross-sectional views of registration marker **40**, which is assumed to define a registration marker frame of reference **50**, herein assumed to comprise an orthogonal set of xyz axes. Marker **40** is formed from a solid substrate **44**, which is opaque to light in the visible and near-visible spectrum, and which is transparent to fluoroscopic radiation. Substrate **44** is typically formed from a hard plastic, such as polycarbonate, but any other solid material which is opaque to light and transparent to fluoroscopic radiation may be used in embodiments of the present invention.
(25) In the illustrated embodiment of marker **40**, substrate **44** is formed as a rectangular parallelepiped **46**, upon which is mounted a pillar **48**.
(26) A plurality of optically reflective, but radiotransparent, discrete elements **54** are disposed on substrate **44**. Elements **54** are hereinbelow, by way of example, assumed to comprise discs, and are also referred to herein as discs **54**. It is understood that said optically reflective and radiotransparent elements may be of different shapes and/or sizes.
(27) Some of the plurality of discs **54** are fixedly attached, typically by cementing, to a two-dimensional (2D) surface **52** of parallelepiped **46**. These discs **54** are formed in a generally rectangular 2D pattern on surface **52**. In addition, an optically reflective disc **54** is also cemented onto pillar **48**, so that there is in totality a three-dimensional (3D) array of discs **54** disposed on the substrate. The 3D array of discs **54** are distributed on 2D surface **52**, and on pillar **48**, so that when marker **40** is illuminated and imaged by camera **50** the discs are easily distinguished from substrate **44**. Furthermore, as explained in more detail below, the arrangement of discs **54** are configured to enable processor **32** to unambiguously determine the orientation and position of frame of reference **50** from the marker image.
(28) The distributed discs **54** are herein assumed to comprise an optical component **56** of marker **40** that forms an optical pattern **58** for the marker. In a particular aspect of the invention optical pattern **58**, comprising the distribution of discs **54**, is implemented so that the pattern has no axis of symmetry and no plane of symmetry. The absence of both an axis and a plane of symmetry in the pattern ensures that the unambiguous determination of the orientation and position of the frame of reference of marker **40** is possible from the marker image for multiple different orientations and positions of the marker, the positions being typically within a region approximately 20 cm from the patient marker.
(29) The description above of optical pattern **58** assumes that discs **54** are configured in three dimensions. However, as long as the pattern has no axis of symmetry and no plane of symmetry, the discs forming the pattern may be arranged in only two dimensions, for example, absent the disc on pillar **48**. Thus, pattern **58** may be formed in at least two dimensions, i.e., in the case of discs **54**,

as a two-dimensional array of the discs or as a three-dimensional array of the discs.
(30) It will be understood that the requirement for discs **54** to be arranged to form a pattern having an absence of both an axis and a plane of symmetry may be achieved using discs of substantially the same size and shape, wherein locations of the discs are selected so that the locations are arranged to have the absence of both an axis and a plane of symmetry. The described pattern is hereinbelow referred to as a unique optical pattern.
(31) Alternatively, the unique optical pattern may be achieved using discs of different sizes and/or shapes. In this case, the locations of the discs may also satisfy the requirement, but this is not a necessity.
(32) A multiplicity of radiopaque elements **60** are disposed in substrate **44** by being embedded in a distribution within parallelepiped **46**. The distribution of elements **60** is arranged in a two dimensional radiopaque pattern **62** such that, as for the pattern of discs **54**, the radiopaque pattern has no axis of symmetry and no plane of symmetry. Because substrate **44** is radiotransparent, and because of the absence of both an axis and a plane of symmetry in radiopaque pattern **62**, a fluoroscopic, typically computerized tomography (CT), scan of the radiopaque elements of marker **40** enables the orientation and position of frame of reference **50** to be unambiguously determined by processor **32** from the fluoroscopic scan. In one embodiment elements **60** comprise spheres which are distributed in a 2D generally rectangular 2D pattern that is substantially the same as the rectangular pattern of discs **54** on surface **52**.
(33) The description above of elements **60** assumes that they are arranged in a radiopaque pattern of two dimensions. However, as long as the pattern has no axis of symmetry and no plane of symmetry, the elements forming the pattern may also be arranged in three dimensions, for example, by incorporation of a radiopaque element **60**A, substantially similar to elements **60**, in pillar **48**. Thus, pattern **62** may also be formed in at least two dimensions, i.e., in the case of elements **60** and **60**A, as a two-dimensional array of elements **60** or as a three-dimensional array of elements **60** and **60**A.
(34) As for discs **54**, it will be understood that the requirement for elements **60** to be arranged to form a pattern having an absence of both an axis and a plane of symmetry may be achieved using elements of substantially the same size and shape, wherein locations of the elements are selected so that the locations are arranged to have the absence of both an axis and a plane of symmetry. The described pattern is hereinbelow referred to as a unique radiopaque pattern.
(35) Alternatively, the unique radiopaque pattern may be achieved using elements of different sizes and/or shapes. In this case, the locations of the elements may also satisfy the requirement, but this is not a necessity.
(36) The X-ray wavelengths of the CT scan are assumed to be in a range of 0.01-10 nm.
(37) The above description of marker **40** assumes that discs **54** and elements **60** have different functionalities—the discs being optically reflective and radiotransparent, and the elements being radiopaque. In an alternative embodiment of marker **40** at least some of discs **54** are configured to have dual functionality by being optically reflective and radiopaque. As for the embodiment described above, in the alternative embodiment discs **54** are configured and distributed on substrate **44** so that an optical image of marker **40** provides an unambiguous determination of the orientation and position of frame of reference **50**, and a fluoroscopic scan of the marker also provides an unambiguous determination of the orientation and position of the frame of reference.
(38) The physical construction of the illustrated embodiment of marker **40**, as a pillar attached to a rectangular parallelepiped, comprising an array of discs **54** and an array of elements **60**, is but one example of possible physical constructions of the marker that enables an unambiguous determination of the marker's position and orientation from a camera image and from a fluoroscopic scan. In a disclosed embodiment, rather than marker **40** comprising pillar **48** mounted on substrate **44**, an indentation (in place of the pillar) is formed within the substrate, and a disc **54** is located on a surface of the indentation.

(39) Other suitable constructions for marker **40** are also considered to be within the scope of the present invention.
(40) For example, the substrate of marker **40**, rather than being formed from a parallelepiped with a pillar or an indentation, may be formed as substantially any conveniently shaped solid object that is opaque to light in the visible and near-visible spectrum and which is transparent to fluoroscopic radiation.
(41) In addition, rather than the optical component of marker **40** being comprised of a plurality of discs **54** arranged in a particular pattern, the component may comprise any array or pattern of optical elements that is attached to the substrate, that is diffusely and/or specularly reflective, and that is configured to have the absence of axes and planes of symmetry described above, so that when imaged in visible or near-visible light an unambiguous determination of the marker's position and orientation may be made.
(42) Referring to FIG. **4**, patient marker **38** is assumed to define a patient marker frame of reference **100**, assumed to comprise an orthogonal set of xyz axes. In the embodiment illustrated in FIG. **4** marker **38** comprises a rectangular parallelepiped substrate **102** to which is attached a tongue **104** used to fixedly connect the substrate to clamp **30**. A center **103** of an upper surface of substrate **102** acts as an origin of the xyz axes.
(43) The connection to clamp **30** is by a removable screw **112**, and the patient marker connects in a predetermined fixed spatial relationship to the clamp using holes **114** which align with studs **116** of the clamp. Substrate **102** comprises a solid opaque material, and may be formed from any convenient material such as polyimide plastic.
(44) A plurality of optically reflective discs **106**, generally similar to discs **54**, are attached, typically by cementing, to an upper 2D surface **110** of substrate **102**. Discs **106**, also referred to herein as reflectors **106**, are formed in a generally rectangular 2D pattern on surface **110**. Discs **106** are distributed so that when illuminated and imaged by camera **42** they are easily distinguished from substrate **102**.
(45) In addition, discs **106** are distributed with respect to an xz plane **120** and a yz plane **122** through origin **103**. xz plane **120** and yz plane **122** are planes of asymmetry. Thus, discs **106** are arranged non-symmetrically with respect to xz plane **120**, so that the distribution of the discs on one side of plane **120** do not mirror (through the plane) the discs on the opposing side of the plane. In addition, discs **106** are arranged non-symmetrically with respect to yz plane **122**, so that the distribution of the discs on one side of plane **122** do not mirror the discs on the opposing side of the plane.
(46) In FIG. **4** discs **106** are shown as being distributed on sides of a rectangle, however, it will be understood that this is but one example for the positioning of the discs on surface **110**. Other distributions of discs **106**, providing that they define planes of asymmetry as described above, are also assumed to be comprised within the scope of the present invention.
(47) Furthermore, it will be appreciated that the physical construction of patient marker **38** described above is by way of example. Thus, embodiments of the present invention comprise any patient marker formed of any conveniently shaped solid opaque substrate to which is attached an optical pattern, the pattern defining planes of asymmetry as described above.
(48) FIG. **5** is a flowchart of steps performed to register patient marker **38** with the anatomy of patient **22** during the initial preparatory stage of a medical procedure illustrated in FIG. **1**, according to an embodiment of the present invention. While the following description assumes, for simplicity, a CT scan, other types of fluoroscopic imaging are also considered to be within the scope of the present invention.
(49) In an initial step **150**, medical professional **26** makes an incision in the back of patient **22**, inserts spinous clamp **30** into the patient, and then clamps the clamp to one or more of the processes of the patient.
(50) In a patient marker step **152**, the medical professional attaches patient marker **38** to spinous

clamp **30**, ensuring that the marker is rigidly attached to the clamp. Marker **38** is attached to clamp **30** so that surface **110**, corresponding to the xy plane of the xyz axes, is approximately parallel to a frontal plane of patient **22**, xz plane of asymmetry **120** is approximately parallel to a sagittal plane of the patient, and so that yz plane of asymmetry **122** is approximately parallel to an axial plane of the patient. As used herein, the term "approximately parallel" as applied to two planes indicates that the planes subtend an angle within a range of ±20° to each other.

(51) In a registration marker step **154**, the professional places registration marker **40** on the skin of the back of the patient, typically as close to the patient's spine as is convenient.

(52) In a camera step **156**, professional **26** adjusts his/her position so that camera **42**, attached to head-mounted display **64** images the registration marker and the patient marker. Professional **26** adjusts their position so that the images formed by camera **42** of the registration marker and of the patient marker are clear images, i.e., that neither marker occludes the other. Typically processor **32** of processing system **28** is configured to verify the acceptability of the two marker images, and if necessary the professional may use and communicate with system **28** to adjust, in an iterative manner, their position and/or that of the registration marker until system **28** provides an indication to the professional that acceptable images are being generated.

(53) Once acceptable images are being generated, a camera image of the two markers is acquired, and is provided to processing system **28**.

(54) In a fluoroscopic scan step **158**, a CT scan of patient **22**, in the vicinity of marker **40** is performed, and processing system **28** acquires the scan. The scan may be performed by inserting patient **22** into a CT scanning system so that marker **40** is scanned. The insertion may be implemented by bringing the CT scanning system to patient **22**, or by transporting the patient to the system. In either case, marker **40** remains in the marker's position of step **156**.

(55) In a scan analysis step **160**, processor **32** analysis the CT scan acquired in step **158**, the scan comprising an image of radiopaque elements **60** and of the anatomy of patient **22**.

(56) From the acquired image, processor **32** calculates the position and orientation of registration marker frame of reference **50**, and registers the frame of reference with the anatomy of the patient. The registration typically comprises a set of vectors P between selected points on registration marker **40** and selected vertebrae of patient **22**. In one embodiment, the registration comprises using a 4×4 homogenous transformation, comprising a 3×3 rotation and a 1×3 translation, that transforms a point in the space of patient **22** to a point in registration marker frame of reference **50**.

(57) In a camera image analysis step **162**, processor **32** analyzes the camera image of patient marker **38** and registration marker **40** acquired in step **156**. From the acquired image, processor **32** calculates the position and orientation of registration marker frame of reference **50**, and the position and orientation of patient marker frame of reference **100**. Once the processor has calculated the positions and orientations of the two frames of reference, it formulates a registration of the two frames of reference as a set of vectors Q describing the transformation of the registration marker frame of reference to the patient marker frame of reference.

(58) In a concluding analysis step **164**, the processor adds the two sets of vectors found in steps **160** and **162** to formulate a registration set of vectors R between the patient marker frame of reference **36** and the patient anatomy, as shown in equation (1):

$$R=P+Q \qquad (1)$$

(59) FIG. **6** illustrates a subsequent stage of the medical procedure, FIG. **7** is a flowchart of steps performed during the subsequent stage, and FIG. **8** shows schematic figures illustrating images generated in the subsequent stage, according to an embodiment of the present invention. In the subsequent stage registration marker **40** has been removed from the back of patient **22**, and medical professional **26** operates on the patient using a surgical tool **190**. The tool is tracked by the HMD processor, by having identifying reflectors **194**, generally similar to reflectors **106**, attached to the tool.

(60) In an initial step **200** of the flowchart of FIG. **7**, the HMD projects visible or invisible light to

patient marker **38** and tool **190**. Camera **42** acquires images of reflectors **106** of the marker, of reflectors **194** of tool **190** and of patient **22** and tool **190**.
(61) The flowchart then branches into two paths, a first path **202** and a second path **204**. Processor **32** implements steps of both paths substantially simultaneously.
(62) In first path **202**, in a three-dimensional (3D) image retrieval step **210**, processor **32** retrieves a 3D stored patient anatomy image of patient **22**, typically comprising a CT image of the patient, from stored images **35**. The processor also retrieves a stored virtual image, also herein termed a stored representation, of tool **190** from the stored images.
(63) In a 3D image presentation step **214**, the processor presents aligned 3D images of the patient anatomy and of the virtual tool image in the head mounted display.
(64) The position of the virtual tool image is determined from reflectors **194**. In order to ensure that the anatomy image and the virtual tool image, projected by the display, align with the anatomy of patient **22** and with the actual tool image, the processor determines the position and orientation of frame of reference **100** of the patient marker from the acquired images of reflectors **106**. The processor applies the registration set of vectors R, found in step **164** of the flowchart of FIG. **5**, to the position and orientation of the marker frame of reference, so as to effect the alignment.
(65) In second path **204**, in a plane identification step **220**, processor **32** analyzes the images of reflectors **106** acquired by camera **42** to identify the position and orientation of xz plane of asymmetry **120** and yz plane of asymmetry **122**. From the images the processor also calculates and stores the height of camera **42** above the xy plane.
(66) From the identified positions and orientations of the planes the processor determines on which side of the planes camera **42** resides. Each plane has two sides, and it will be understood that the two planes divide the volume around marker **38** into four regions, the camera residing in one of four regions.
(67) In a tool reflector step **224** the processor analyzes the images of reflectors **194** to find the position and orientation of tool **190**.
(68) In an image retrieval step **228** the processor retrieves a stored virtual image of the tool. The processor also retrieves, from the stored 2D images, images of the patient anatomy at the tool position, and parallel to the axial and sagittal planes of the patient.
(69) In an image presentation step **232**, the processor uses the retrieved images to generate a combined image of the patient anatomy with a representation of the tool superimposed on the patient anatomy, from a point of view of the camera, i.e., from a point of view in the plane sides identified in step **220**.
(70) The processor presents the combined image in HMD **64** for viewing by professional **26**.
(71) By presenting images in HMD **64** according to the point of view of camera **42**, embodiments of the present invention present correctly oriented images to operator **26**, who is wearing the HMD. It will also be understood that the correct orientation is determined according to the position of the operator **26** with respect to the patient, i.e., whether the operator is to the left or right of the patient, and whether the operator is on a lower or upper side of the patient.
(72) FIG. **8** shows schematic illustrations of images generated in step **232**, according to an embodiment of the present invention.
(73) A diagram **300** illustrates an image **304**A of tool **190** superimposed on an image **308**A of the patient anatomy, from a point of view in a left side of a sagittal plane of patient **22**, and a diagram **312** illustrates an image **304**B of tool **190** superimposed on an image **308**B of the patient anatomy, from a point of view in a right side of the patient sagittal plane. The two diagrams are mirror images of each other, and use a stored image **304** of tool **190**. The two diagrams also use a stored image **308** of the patient anatomy that is parallel to the patient sagittal plane at an identified position of tool **190**.
(74) A diagram **320** illustrates an image **304**C of tool **190** superimposed on an image **324**A of the patient anatomy, from a point of view in a lower side of an axial plane of patient **22**, and a diagram

330 illustrates an image **304**D of tool **190** superimposed on an image **324**B of the patient anatomy, from a point of view in an upper side of the patient axial plane. As for diagrams **300**, **312**, the two diagrams **320**, **330** are mirror images of each other, and use stored image **304** of tool **190**. Diagrams **320**, **330** use a stored image **324** of the patient anatomy that is parallel to the patient axial plane at the identified position of tool **190**.

(75) Returning to the flowchart of FIG. **7**, it will be appreciated that professional **26** may select which images, referred to in steps **214** and **232**, are rendered for viewing in the head-mounted display. Thus the professional may view either the 3D images of step **214**, or the 2D images of step **232**, or both images simultaneously.

(76) FIG. **9** is a schematic top-down view of surface **110** of marker **38**, showing the x, y, and z axes of the marker, as well as xz plane **120** and yz plane **122**.

(77) As operator **26** moves from one side of xz plane **120** to the other side, then following on from step **232** of the flowchart of FIG. **7** together with the diagrams of FIG. **8**, the images presented to the operator are mirror images of each other. The mirroring is also true when the operator moves from one side of yz plane **122** to the other side.

(78) A disclosed embodiment of the present invention places a limitation on the mirroring described above when moving from one side of a plane to another, in order to reduce jitter in the presented images when the operator is close to the plane. In order to reduce jitter, the processor constructs transition regions around xz plane **120** and other transition regions around yz plane **122**. The following description is for the transition region around xz plane **120** and to the right of yz plane **122**.

(79) Processor **32** constructs a first plane **402** containing and terminating at the z axis, and at an angle $+\theta$ from xz plane **120**, and a second plane **404** containing and terminating at the z axis, and at $-\theta$ from xz plane **120**. In one embodiment $\theta \leq 10°$. The two planes form respective wedge-shaped regions **412**, **414** with xz plane **120**, and these two wedge-shaped regions comprise the transition region around xz plane **120** and to the right of yz plane **122**.

(80) If the movement across xz plane **120** includes both wedge-shaped regions being crossed, by the HMD and the attached camera of the operator, or begins from within one of the wedge-shaped regions and crosses the other one, then the mirroring as described above is implemented.

(81) However, if the movement across the xz plane does not comply with the movements above, e.g., the movement only crosses one wedge-shaped region and stops in the other region, or only moves between wedge-shaped regions, then no mirroring is implemented.

(82) For a transition region around xz plane **120** and to the left of yz plane **122**, the processor constructs two planes making angles $\pm\theta$ with the xz plane, generally similar to planes **402** and **404**, so as to form two more wedge-shaped regions terminating at the z axis and to the left of the yz plane.

(83) The processor constructs the same type of transition regions for yz plane **122**. Thus, for a transition region around yz plane **122** and above xz plane **120**, the processor constructs two planes making angles A with the yz plane, generally similar to planes **402** and **404**, so as to form two wedge-shaped regions terminating at the z axis and above the xz plane.

(84) Similarly, for a transition region around yz plane **122** and below the xz plane, the processor constructs two planes making angles A with the yz plane, generally similar to planes **402** and **404**, so as to form two wedge-shaped regions terminating at the z axis and below the xz plane.

(85) There are thus a total of four transition regions distributed symmetrically about the z-axis, each transition region comprising two wedge-shaped regions.

(86) As for the movement for the illustrated transition region, if movement across either of planes **120** or **122** includes both wedge-shaped regions being crossed, by the HMD and the attached camera of the operator, or begins from within one of the wedge-shaped regions and crosses the other one, then the mirroring is implemented.

(87) However, if the movement across either of the planes does not comply with the movements

above, then no mirroring is implemented, i.e., mirroring is precluded.
(88) Another disclosed embodiment of the present invention places another limitation on the mirroring described above. In this embodiment, when the operator moves to look over patient **22**, mirroring is also precluded. To preclude mirroring for this embodiment, the processor checks if the camera height, measured in step **220** of the flowchart of FIG. **7** has changed, as is the case if operator **26** moves her/his head to look over patient **22**. I.e., if the camera height changes, no mirroring is implemented regardless of whether the xz plane or the yz plane have been crossed.
(89) FIG. **10** is a schematic illustration of the subsequent stage of the procedure, when two operators use an imaging system **320**, according to an embodiment of the present invention. Apart from the differences described below, the operation of system **320** is generally similar to that of system **20** (FIGS. **1-9**), and elements indicated by the same reference numerals in both systems **20** and **320** are generally similar in construction and in function.
(90) In contrast to system **20**, system **320** is used by operator **26** and a second operator **326**. Second operator **326** wears an HMD **364**, and a camera **342** is fixedly attached to the HMD. HMD **364** and camera **342** are respectively substantially similar in construction and function to HMD **64** and camera **42**. However, camera **342** is typically not used to perform the registration described in the flowchart of FIG. **5**, since this is provided by camera **42**.
(91) Images generated in HMD **364** are substantially as described in the flowchart of FIG. **7**. Thus, images presented in HMD **364** are oriented according to the point of view of camera **342**, i.e., according to whether operator **326** is to the left or right of patient **22**, and according to whether the operator is on the lower or upper side of the patient.
(92) It will be understood that by presenting images in a head-mounted display according to the point of view of the camera attached to the display, embodiments of the present invention present correctly oriented images to a wearer of the head-mounted display. It will also be understood that the correct orientation is determined according to the position of the wearer of the HMD with respect to the patient, i.e., whether the wearer is to the left or right of the patient, and whether the wearer is on a lower or upper side of the patient.
(93) It will be further understood that for cases where there is more than one HMD, each being worn by a respective wearer, embodiments of the present invention operate simultaneously and independently to present correctly oriented images to each wearer, according to the position of the respective wearer with respect to the patient. A wearer on the right side of the patient and a wearer on the left side of the patient are presented with mirror images based on anatomy images parallel to the patient sagittal plane; similarly a wearer on the lower side of the patient and a wearer on the upper side of the patient are presented with mirror images based on anatomy images parallel to the patient axial plane.
(94) It will thus be appreciated that the embodiments described above are cited by way of example, and that the present invention is not limited to what has been particularly shown and described hereinabove. Rather, the scope of the present invention includes both combinations and subcombinations of the various features described hereinabove, as well as variations and modifications thereof which would occur to persons skilled in the art upon reading the foregoing description and which are not disclosed in the prior art.

Claims

1. An imaging system, comprising: a first head-mounted display; a second head-mounted display; a patient marker configured to be attached to a human subject and defining a first plane and a second plane, the patient marker comprising optically reflective elements disposed on opposing sides of the first plane in a non-symmetrical arrangement with respect to the first plane and on opposing sides of the second plane in a non-symmetrical arrangement with respect to the second plane, wherein the patient marker is configured such that, when attached to the human subject, the first

plane will make an angle between +20° and −20° with a sagittal plane of the human subject, and the second plane will make an angle between +20° and −20° with an axial plane of the human subject; a memory configured to store a graphical representation of a tool used in a procedure performed by a wearer of the first head-mounted display on the human subject, and an image of anatomy of the human subject; a first camera attached to the first head-mounted display and configured to acquire a first input image of the patient marker and of the tool; a second camera attached to the second head-mounted display and configured to acquire a second input image of the patient marker and of the tool; and one or more processors configured to: analyze the first input image to identify the first plane and the second plane, and to identify at least one of: whether the first camera is located on a first side or second side of the first plane, or whether the first camera is located on a first side or second side of the second plane; render to the first head-mounted display the image of the anatomy of the human subject with the graphical representation of the tool superimposed thereon from a point of view based on the analysis of the first input image; analyze the second input image to identify the first plane and the second plane, and to identify at least one of: whether the second camera is located on the first side or second side of the first plane, or whether the second camera is located on the first side or second side of the second plane; and render to the second head-mounted display the image of the anatomy of the human subject with the graphical representation of the tool superimposed thereon from a point of view based on the analysis of the second input image.
2. The imaging system of claim 1, wherein the first plane is orthogonal to the second plane.
3. The imaging system of claim 1, wherein the patient marker comprises a substrate, and the optically reflective elements are disposed on an upper surface of the substrate.
4. The imaging system of claim 3, wherein the patient marker further comprises a plurality of radiopaque elements disposed in the substrate on opposing sides of the first plane in a non-symmetrical arrangement with respect to the first plane and on opposing sides of the second plane in a non-symmetrical arrangement with respect to the second plane.
5. The imaging system of claim 1, wherein the image of the anatomy of the human subject is a two-dimensional image.
6. The imaging system of claim 1, wherein: the tool comprises a reflector attached thereto, a position of the tool in the image rendered to the first head-mounted display is based on detection of a position of the reflector in the analysis of the first input image, and a position of the tool in the image rendered to the second head-mounted display is based on detection of a position of the reflector in the analysis of the second input image.
7. The imaging system of claim 1, wherein the one or more processors are further configured to: analyze additional input images acquired by the first camera to identity if the first camera has moved to a different side than identified from the analysis of the first input image; and analyze additional input images acquired by the second camera to identity if the second camera has moved to a different side than identified from the analysis of the second input image.
8. The imaging system of claim 7, wherein the one or more processors are further configured to: detect that the first camera has moved to a different side than identified from the analysis of the first input image; and responsive to the detection, render to the first head-mounted display the image of the anatomy of the human subject with the graphical representation of the tool superimposed thereon from a point of view based on the detection.
9. The imaging system of claim 7, wherein the one or more processors are further configured to: detect that the second camera has moved to a different side than identified from the analysis of the second input image; and responsive to the detection, render to the second head-mounted display the image of the anatomy of the human subject with the graphical representation of the tool superimposed thereon from a point of view based on the detection.
10. An imaging system, comprising: a first head-mounted display; a second head-mounted display; a first camera attached to the first head-mounted display and configured to acquire a first input

image of a patient marker attached to a human subject and of a tool used in a procedure performed by a wearer of the first head-mounted display on the human subject, the patient marker comprising optically reflective elements disposed on opposing sides of a first plane in a non-symmetrical arrangement with respect to the first plane, wherein the first plane is configured to make an angle between +20° and −20° with a sagittal plane of the human subject, and on opposing sides of a second plane in a non-symmetrical arrangement with respect to the second plane, wherein the second plane is configured to make an angle between +20° and −20° with an axial plane of the human subject; a second camera attached to the second head-mounted display and configured to acquire a second input image of the patient marker and of the tool; a memory configured to store a graphical representation of the tool, and an image of anatomy of the human subject; and one or more processors configured to: analyze the first input image to identify the first plane and the second plane, and to identify at least one of: whether the first camera is located on a first side or second side of the first plane, or whether the first camera is located on a first side or second side of the second plane; render to the first head-mounted display the image of the anatomy of the human subject with the graphical representation of the tool superimposed thereon from a point of view based on the analysis of the first input image; analyze the second input image to identify the first plane and the second plane, and to identify at least one of: whether the second camera is located on the first side or second side of the first plane, or whether the second camera is located on the first side or second side of the second plane; and render to the second head-mounted display the image of the anatomy of the human subject with the graphical representation of the tool superimposed thereon from a point of view based on the analysis of the second input image.
11. The imaging system of claim 10, wherein the first plane is orthogonal to the second plane.
12. The imaging system of claim 10, wherein the patient marker comprises a substrate, and the optically reflective elements are disposed on an upper surface of the substrate.
13. The imaging system of claim 12, wherein the patient marker further comprises a plurality of radiopaque elements disposed in the substrate on opposing sides of the first plane in a non-symmetrical arrangement with respect to the first plane and on opposing sides of the second plane in a non-symmetrical arrangement with respect to the second plane.
14. The imaging system of claim 10, wherein the image of the anatomy of the human subject is a two-dimensional image.
15. The imaging system of claim 10, wherein: the tool comprises a reflector attached thereto, a position of the tool in the image rendered to the first head-mounted display is based on detection of a position of the reflector in the analysis of the first input image, and a position of the tool in the image rendered to the second head-mounted display is based on detection of a position of the reflector in the analysis of the second input image.
16. The imaging system of claim 10, wherein the one or more processors are further configured to: analyze additional input images acquired by the first camera to identity if the first camera has moved to a different side than identified from the analysis of the first input image; and analyze additional input images acquired by the second camera to identity if the second camera has moved to a different side than identified from the analysis of the second input image.
17. The imaging system of claim 16, wherein the one or more processors are further configured to: detect that the first camera has moved to a different side than identified from the analysis of the first input image; and responsive to the detection, render to the first head-mounted display the image of the anatomy of the human subject with the graphical representation of the tool superimposed thereon from a point of view based on the detection.
18. The imaging system of claim 16, wherein the one or more processors are further configured to: detect that the second camera has moved to a different side than identified from the analysis of the second input image; and responsive to the detection, render to the second head-mounted display the image of the anatomy of the human subject with the graphical representation of the tool superimposed thereon from a point of view based on the detection.