Optimizing the Arrangement of Fixed Light Modules in New Autonomous Surgical Lighting Systems

Andre Mühlenbrock[a], Timur Cetin[b], Dirk Weyhe[b], and Gabriel Zachmann[a]

[a]University of Bremen, Faculty of Computer Science, Germany
[b]Carl von Ossietzky University of Oldenburg, Dept. of Visceral Surgery, Germany

ABSTRACT

Several novel autonomous lighting systems for illuminating the surgical site (e.g. SmartOT) consist of a large number of swiveling light modules placed on the ceiling instead of two or three movable OR lights. For such a new type of lighting system for operating rooms, the initial placement of the light modules is of great importance, since the light modules cannot be moved during surgery. For this reason, we present a novel approach for optimizing the arrangement of light modules in a new autonomous lighting system that exploits the special characteristics of an operating room and the surgeries that take place there by taking into account occluding geometry (e.g., surgeons and medical staff) via point cloud recordings.

We have implemented a function that provides the brightness at the surgical site for an arbitrary arrangement of light modules at a given time of a point cloud recording. Based on this brightness function, we defined a fitness function which we used for optimization. Using cross-validation, we compared the results of three optimization algorithms (Greedy, SGA, SADE) to naive arrangements of light modules. By performing these optimizations on point cloud recordings of nine real open abdominal surgeries, we obtain arrangements that achieve up to 41 % higher minimum brightness during surgery compared to naive arrangements.

Keywords: Surgery lighting, optimal lighting, open surgery, depth sensors, point clouds, optimization

1. INTRODUCTION

OR lights (SLS) are still widely used in traditional open surgery. However, several problems have been identified with the use of these lights: On the one hand, frequent repositioning of the OR lights is required, resulting in many small interruptions during the surgery. Furthermore, many other aspects of OR lights have been identified as requiring improvement by surgeons and medical staff, concerning the illumination and usability.[1,2] For this reason, new lighting systems are being researched and developed to eliminate the need for frequent manual adjustments and the problems associated with them.

Teuber et al. investigated the possibility of eliminating the need for manual adjustment using motor-driven surgical lights that automatically align with a surgical site.[3] The OR lights were to be controlled by a central computer, which recognized the geometry of the surgeons and medical staff via depth sensors and could thus take into account the shadows cast on the site. The optimization of the OR light positions during surgery is a multi-objective optimization, in which, in addition to optimal illumination, as little movement as possible should be generated to not distract surgeons.[4]

Other lighting concepts solve the problem of distraction and hazards caused by automatically moving OR lights by attaching fixed but rotatable light modules to the ceiling, such as the SmartOT project[*], or by integrating them into the ceiling, as in the Optimus CelestialTM Surgical Lighting System [†]. However, since individual light modules in these systems can only be rotated and not moved during surgery, the initial positioning of the light modules is of great importance - after all, light modules that are usually located behind the surgeon or medical staff can do little to illuminate the surgical site. In order to automatically find those light modules that

Further author information: (Send correspondence to Andre Mühlenbrock)
Andre Mühlenbrock: E-mail: muehlenb@uni-bremen.de, Telephone: +49 (0)421 218 63 998

[*]See https://www.smart-ot.de/

[†]See https://www.optimus-ise.com/components/celestial-surgical-lighting-system/

can contribute little to the illumination of the surgical site in the total surgical procedure and to automatically optimize an entire arrangement of light modules, we have developed an optimization procedure, which we present in this paper. This optimization procedure is applicable to individual operating rooms and takes advantage of the specific characteristics of the room and the surgeries that take place there by taking into account shadowing geometry (e.g., surgeon and medical staff) via point cloud recordings of real surgeries.

The optimization we present allows to determine a number as well as an optimal arrangement of light modules in order to ensure a desired minimum and/or average brightness during the entire surgical procedure. Compared with naïve arrangements, it makes it possible to dispense with light modules while maintaining the same illumination power, or to enable a higher illumination power with a predefined number of light modules.

2. OPTIMIZATION PROCEDURE

For our optimization procedure, depth recordings of real open surgeries in the corresponding operating room are a prerequisite, which can be obtained by using depth sensors such as the Microsoft Kinect v2 or the Microsoft Azure Kinect. Depending on the characteristics of the operating room, multiple depth sensors might be required to record the occluding geometry as completely as possible during surgery.

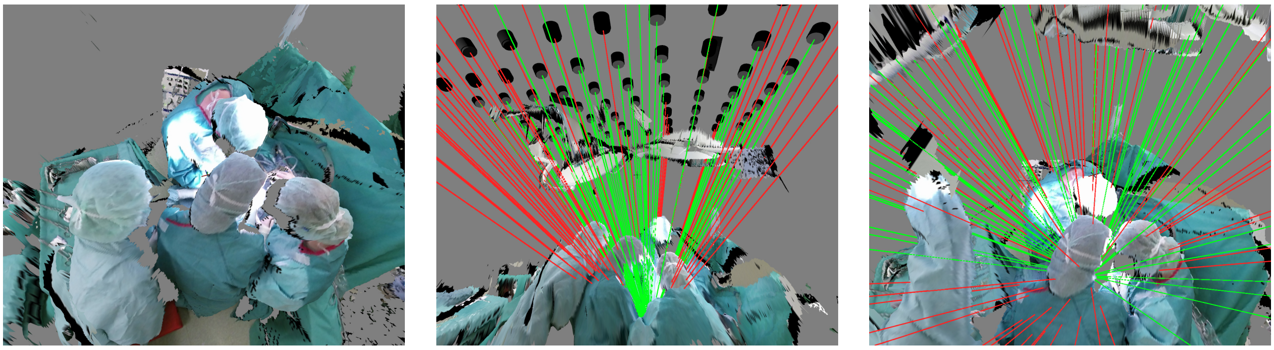

Figure 1. Depth recordings of a surgery projected as point cloud in our 3D simulation software. By shooting rays from light modules at the ceiling to the surgical site, we are testing whether the light would be blocked by occluding geometry (red rays) or is reaching the surgical site (green rays). The occlusion test is internally performed against a height map while the original three overlapping registered point clouds are displayed here.

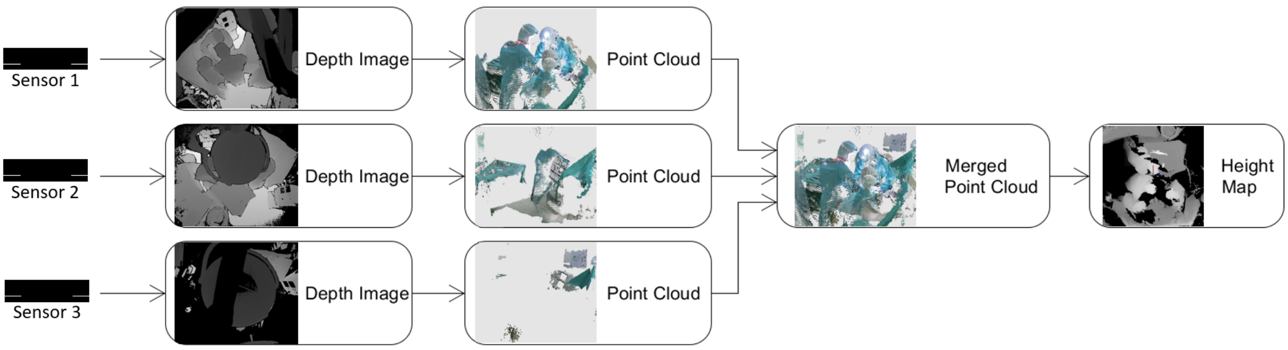

Figure 2. Preprocessing depth images of multiple depth sensors to obtain a common height map. This is done for each frame that is considered in the optimization procedure.

Since high-performance collision checks on the depth recordings are necessary for the optimization procedures in order to check whether the light from a light module is blocked by occluding geometry on its way to the surgical site (see Fig. 1), preprocessing of the depth image recordings is necessary. For all frames of all depth recordings to be considered in the optimization, we proceed as follows: First, we transform the depth pixels into 3D space and obtain a point cloud for each depth sensor. The depth sensors are assumed to be extrinsic calibrated in the operation room. We then project the point cloud of each depth sensor onto a common 2D height map that stores only the height values of the occluding geometry in the area around the OR table (see Fig. 2). In this way, we obtain a set H of height maps in which each height map $h_i \in H$ contains the occluding geometry at a given time i of a surgery.

The model that underlies the optimization consists of:

- L: a variable set of light module positions $l_i \in L$. This set is altered during the optimization.
- H: an invariant set of height maps which are considered in the optimization, in which $h_i \in H$ represents a single height map of a surgery recording at a given time i.
- $s(hi)$: a function that returns the center position of the surgical site for a height map h_i. These positions have to be manually defined or automatically determined for each surgery recording.

We have implemented a function called $brightness(L, h_i)$ that returns a brightness value at position $s(h_i)$ for a given light module arrangement L and a height map h_i. Our implementation uses a simulated light profile of a real light module prototype in the SmartOT project and considers Lambert's cosine law while assuming a flat sensor with a normal that is parallel to the up-vector. Using this brightness function $brightness(L, h_i)$, we define the fitness function for optimization which returns the minimum brightness over all considered frames:

$$f_{\text{Min}}(L, H) = \min(\text{brightness}(L, h_0), ..., \text{brightness}(L, h_n))$$

Note that if we would use the average brightness for the optimization, i.e. define a fitness function f_{AVG}, it might be possible that underrepresented situations and surgery types are illuminated worse and that primarily overrepresented situations and surgery types are optimized, because the overrepresentation nevertheless increases the fitness value. We elliminate this problem when using the fitness function f_{Min}, since optimization is always first performed on the frame(s) in which we find the worst illumination of the surgical site.

In the following, we basically distinct between two different optimization problems: While in (a) the *fixed-layout problem*, possible positions are given by a layout and only the n best positions have to be selected, in (b) the *free-layout problem*, the positions can be freely chosen by the optimization algorithm, only not falling below a minimum distance between the lights modules.

3. STUDY

To investigate the effect of optimizing the light module positions compared to naïve arrangements, we made depth recordings of nine real open abdominal surgeries, listed in Table 1. For this purpose, three Microsoft Kinect v2 were mounted on the ceiling of an operating room (see Fig. 3), which were registered (calibrated extrinsically) to each other using our lattice registration procedure[5]. The number of three depth sensors was necessary to ensure that at least one sensor would always have a clear view of the operating table throughout the surgical procedure and would not be blocked by one of both OR lights which were used.

All surgeries were conducted at the University of Oldenburg's department of visceral surgery, located at PIUS-Hospital, Oldenburg. During the surgeries, illumination of the surgical site was archived by a standard surgical lighting system (DR. Mach, LED-3) fixed to the ceiling. Surgeries were selected to be open, abdominal surgeries (no laparoscopic surgeries were recorded due to different lighting demands during laparoscopy) with an expected duration of more than 60–90 minutes, i.e. no short procedures were recorded. Surgeries included gastrectomy, bowl surgeries (including preparation of ileostomy/colostomy) and hepatic tumor removal. Surgeries were also selected for standard placement of medical personal around the operating table, i.e. having the head surgeon on the right-hand side of the table while the assisting surgeon and the instrumenting nurse were located on the opposite side of the surgical table within the sterile field. This placement of the medical personal around the patient is the most common and was chosen as it represents the majority of abdominal surgeries, yet changes in location of the personal (temporary or for the whole duration of the procedure) are possible due to necessity during the surgery.

Figure 3. We used three Microsoft Kinect v2 (red) to create the depth recordings mounted on the ceiling of the surgery room at the PIUS-Hospital, Oldenburg.

Table 1. Depth recordings of nine open abdominal surgeries made at the PIUS Hospital Oldenburg which were used for optimization. Note that we only used frames from the active surgery procedure and not included frames where nothing was visible or only preparation was done. In the first three surgeries, the recordings were stopped before the surgery actually ended for memory reasons and are thus not entirely complete.

Item	Total Recording Length	Considered Frames	Note
Surgery 1	2:08 h	36	Incomplete
Surgery 2	4:02 h	87	Incomplete
Surgery 3	3:00 h	56	Incomplete
Surgery 4	3:28 h	57	Complete
Surgery 5	2:24 h	54	Complete
Surgery 6	3:27 h	55	Complete
Surgery 7	5:45 h	55	Complete
Surgery 8	3:00 h	80	Complete
Surgery 9	3:11 h	39	Complete

Since the conventional OR lights are partially visible in the depth recordings, we ignored all points in the point cloud that were above a height of 1.95 m in the room when pre-calculating the height map. In this way, the conventional OR lights were filtered out of the height map and were not present as blocking geometry during the optimization. To position the virtual sensor, we manually determined the approximate center of the site in each surgery using the point cloud recording. In our brightness(L, h_i) function, we then automatically select the site position of the particular surgery from which the height map h_i originated as the position for the virtual sensor. Due to the feasibility in terms of computation time, we only considered one frame every two minutes of the active surgery procedures during optimization (see Table 1).

To optimize (a) the *fixed-layout problem*, we implemented a greedy optimization algorithm, which starts with a larger number of light modules than targeted. In each iteration step the respective light module whose removal has the least adverse effect on the fitness function is removed. To identify this light module, all possibilities for the removal of a single light module are tested.

For (b) the *free layout problem*, we have chosen an implementation where the parameters to be optimized are defined by the x- and y-positions of all light modules. With an arrangement of 50 light modules to be optimized, this results in a number of 100 parameters. The height (i.e. the z-position) of the light modules was fixed and was chosen to be 2 meters above the site of the first recorded surgery. We implemented a distance constraint for light modules by decreasing the fitness function for each module which undercuts a distance of 32 cm to other modules.

A large range of heuristic optimization algorithms can be utilized for optimizing the *free layout problem*.

When initially testing various heuristic optimization algorithms of the C++ library pagmo2[6], we observed that the Simple Genetic Algorithm (SGA) and the Self-adaptive Differential Evolution (SADE) converged to a reasonable optimum the fastest, which we will limit to in the following for resource reasons. SGA is stated to be a custom implementation of a genetic algorithm in pagmo2 which allows to choose own selection crossover types, selection schemes and mutation (we used "exponential", "tournament" and "polynomial"). SADE is stated to be the differential evolution (DE) algorithm by Storn and Price[7], which has been extended by two variants of parameter self-adaptation from which we use the iDE variant, which is mainly influenced by Elsayed et al.[8]

Table 2. List of optimizations considered in the cross-validation process. Note that the number of light modules is iteratively reduced using the *fixed-layout problem* while the number of light modules is unchanged when using the *free-layout problem*.

			Light Module Count		
Name	**Algorithm**	**Type**	**Initial**	**Target**	**Initial Arrangement**
Greedy (Grid)	Greedy	Fixed-Layout Problem (a)	100	50	G100 (see Fig. 4)
Greedy (Hex)	Greedy	Fixed-Layout Problem (a)	95	50	H95 (see Fig. 4)
SGA	SGA	Free Layout Problem (b)	50	50	Random
SADE	SADE	Free Layout Problem (b)	50	50	Random

To compare both optimizations problems and the algorithms, we performed a leave-one-out cross-validation where we use each surgery as a single dataset. In this type of cross-validation, each data set is used once as a test set, while the union of the remaining eight data sets is used as a train set. This way, we examine how the light module configurations of different optimization algorithms perform on surgeries for which they are not optimized and are able to detect overfitting. The optimizations which we considered in the cross validation are listed in Table 2.

4. RESULTS

In a preliminary analysis, we calculated how often light from different positions on the ceiling reaches the surgical site with our point cloud recordings and plotted this as a heat map for each individual surgery (see Figure 5). In most surgeries, two main areas stand out to the left and right of the site, from which light frequently reaches the site – these are areas where the conventional OR lights are often located during the surgeries. In particular, on the sides of the operating table where medical staff is standing, the light more often does not reach the site – this is consistent with the assumption that it is less effective to position light modules behind areas where surgeons medical staff are usually standing.

We evaluated four naïve arrangements (G100, H95, G49 and H46) for comparison with optimized arrangements. The naïve arrangements G100 and G49 describe a grid-like arrangement of 10 x 10 lights spaced 32 cm apart and 7 x 7 lights spaced 48 cm apart, respectively, so that both arrangements fill an equal area on the ceiling. Arrangements H46 and H95, on the other hand, describe hexagonal arrangements, also spaced 48 cm and 32 cm apart. These naïve arrangements as well as the results of the first optimizations are shown in Figure 4.

Our results (see Table 3) show that both the *fixed-layout problem* and the *free-layout problem* achieve considerably higher minimum brightness over all frames compared to naïve arrangements. Comparing the naïve grid-like arrangement G49 with the optimized Greedy (Grid) arrangements, we find in average a 41 % increase from 307 klx to 433 klx in minimum brightness normalized over the number of lights. Comparing the hexagonal arrangement H46 and Greedy (Hex), we find a normalized increase in minimum brightness of 37 % from 333 klx to 456 klx. These arrangements are the result of the *fixed-layout problem*. While the results of the *free-layout problem* also perform better than the naïve arrangements with a minimum brightness of 387 klx and 379 klx, the increase of the minimum brightness was in average noticeable lower compared to the optimizations on the *fixed-layout problem*.

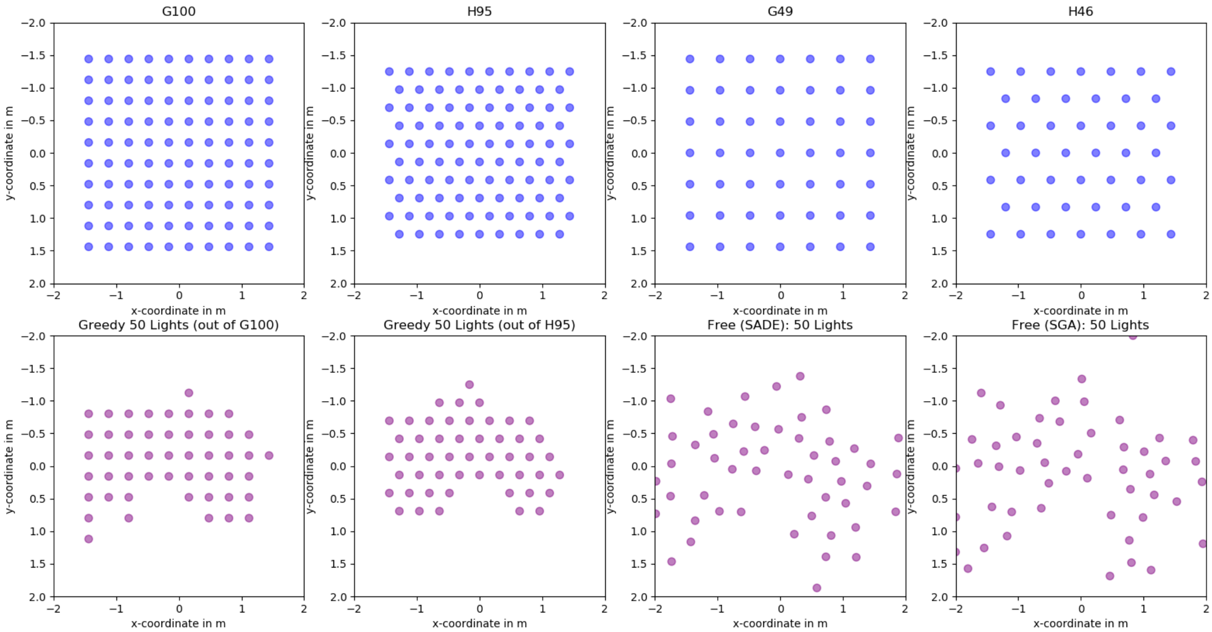

Figure 4. Illustration of the arrangements used in the cross-validation for surgery 1. While the upper arrangements (blue) were used for all surgeries, the lower arrangements (purple) are the result of the optimization on surgery 2 – 9 (to test on surgery 1) and differ slightly for each surgery..

Table 3. Cross-validation results on test sets: Minimum brightness on test sets for different light module arrangements. To allow comparison, we calculated a normalized mean (*), which scales the previously calculated mean to 50 assumed lights. The "Rel. to G49 (*)" row indicates the performance increase compared to the arrangement G49. (All brightness values are given in kilolux (klx))

		Naïve Arrangements				**Optimized Arrangements**			
Test Set	**Train Set**	**G49**	**G100**	**H46**	**H95**	**Greedy (Grid)**	**Greedy (Hex)**	**SADE**	**SGA**
Num Lights	-	49	100	46	95	50	50	50	50
Surgery 1	2-9	365	756	367	829	498	484	438	423
Surgery 2	1, 3-9	289	608	307	649	467	501	372	427
Surgery 3	1-2, 4-9	336	721	359	735	409	404	378	409
Surgery 4	1-3, 5-9	330	649	330	668	453	515	419	392
Surgery 5	1-4, 6-9	260	579	276	646	375	403	312	311
Surgery 6	1-5, 7-9	285	631	293	648	371	415	394	347
Surgery 7	1-6, 8-9	309	588	320	653	437	447	386	369
Surgery 8	1-7, 9	267	551	245	543	412	422	379	345
Surgery 9	1-8	268	628	262	643	471	509	407	385
Mean	-	301	634	306	668	443	456	387	379
SD	-	36	67	42	78	44	47	35	39
Mean (*)	-	**307**	**317**	**333**	**352**	**433**	**456**	**387**	**379**
Rel. to G49 (*)	-	**0 %**	3 %	8 %	14 %	**41 %**	48 %	26 %	23 %

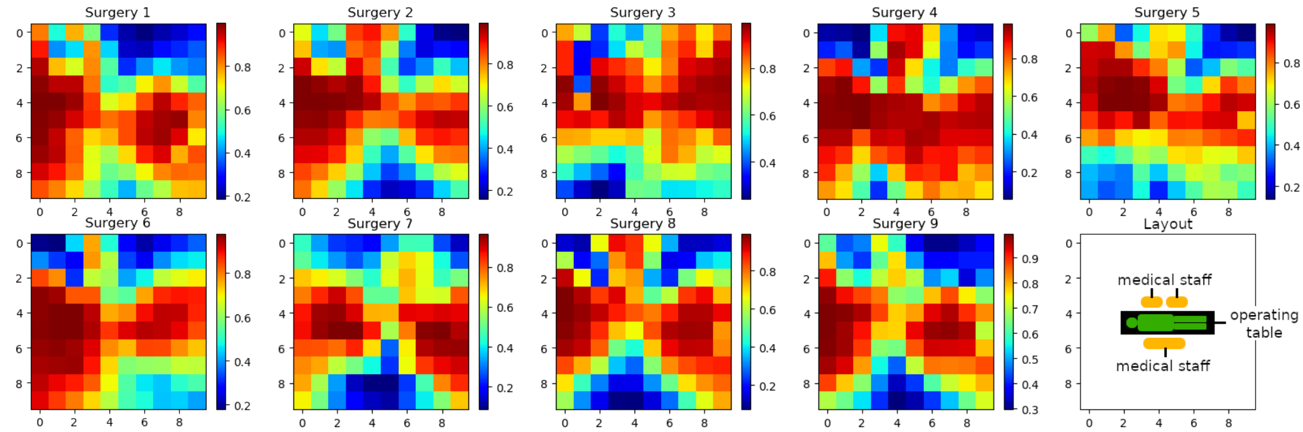

Figure 5. Relative frequencies of how often a light ray reaches the surgical area during surgery from a position on the ceiling of the operating room (evaluating one frame per second of our surgery recordings).

The results for SGA and SADE we presented in Table 3 were obtained with the arrangement we got after 15000 optimization iteration in every single optimization. After this number of iterations, only little change in the arrangement took place; in particular, the minimum brightness did not seem to improve on average (see Fig. 6).

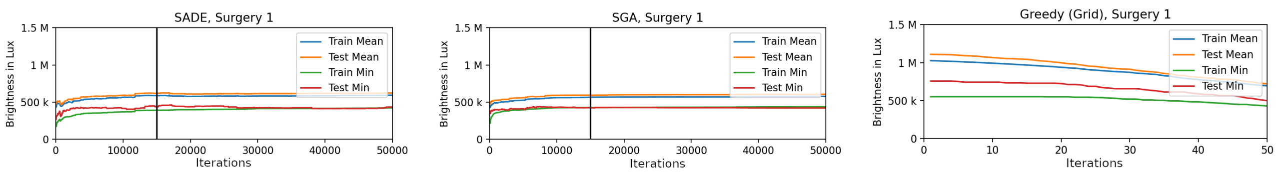

Figure 6. Optimization results over the number of iterations. Note that both SADE and SGA are heuristic optimization algorithms which try to improve the result by repositioning the 50 light modules. Compared to them, the Greedy (Grid) optimization starts with 100 grid-like arranged modules and simply removes a single light module in each iteration step, whose removal has the least adverse effect on the fitness function.

5. DISCUSSION

Our results suggest that optimization can be very useful in such new lighting systems and might generalize well for different surgeries. In direct comparison between the naïve G49 and H46 arrangements with the arrangements of the greedy optimization, we obtain significantly better minimum brightness values not only on average, but in every single surgery (see Table 3).

It might be surprising that the algorithms on the *fixed-layout problem* perform better than the algorithms on the *free-layout problem*, since it is basically possible to arrive at all possible arrangements with the *free-layout problem* that can be arrived at with the *fixed-layout problem*. However, the reverse is not true, since with the *fixed-layout problem* the light modules cannot be freely positioned after all. When we look not only at the results on the test set but also at the results on the train set (see Fig. 7), we see that SADE and SGA are inferior to the Greedy algorithm on the train set, too. This suggests that the combination of problem implementation and algorithms used might not be optimally chosen in the case of the *free-layout-problem*. Also, the distance constraint might have hindered the optimization process. However, we must also take into account that the search space is many times larger in the *free-layout problem* due to the almost endless possibilities of positions for the light modules. This makes the *free-layout problem* much more challenging to optimize compared to the *fixed-layout problem* in general.

From a practical point of view, the fixed layout problem might be more relevant, since possible positions for light modules are often constrained – e.g. by the scaffolding used to attach the light modules or by sockets

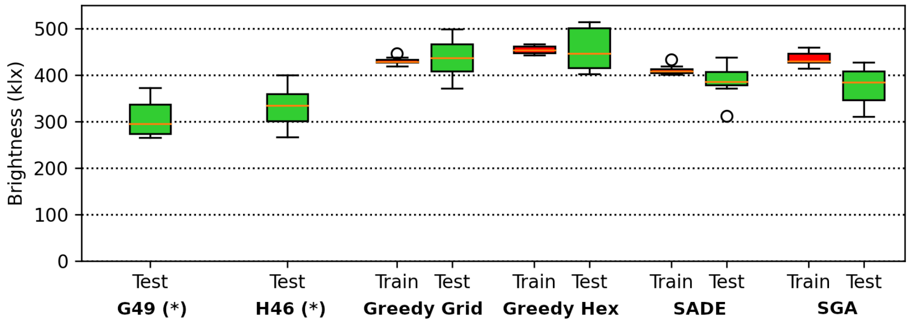

Figure 7. Cross-validation results on train and test sets: Average of minimum brightness of all surgeries on train set (red) and test set (green).

attached to the ceiling into which the light modules can be plugged. We suggest to take optimization into account when designing a lighting system. In such a lighting system, sockets could generally be installed in the ceiling (e.g. in the form of the G100 arrangement), into which only the required number of lighting modules is then inserted in the arrangement of the optimization result. This would allow easy repositioning of the light modules if the range of surgeries performed in the OR room were to change significantly.

It may sound like a lot of effort to install depth sensors and make recordings to optimize the lighting system to the characteristics of an operating room. Note, however, that such depth sensors are already integrated in lighting systems like the SmartOT project, which could automatically write out a point cloud during surgery e.g. every minute (without color information and metadata for privacy reasons) to be able to perform both (a) general optimizations across all OR rooms of a certain type to determine an optimal initial arrangement at first installation and (b) subsequent optimization on the respective OR rooms.

We provide the used depth recordings of nine open abdominal recordings for download[‡] (without color or meta information for privacy reasons).

6. LIMITATIONS

Although our results provide strong indications that optimization might be useful, our results so far still contain some uncertainties. These are:

1. **Non-optimal algorithms:** The optimization algorithms we use are known to be non-optimal and do not necessarily return the global optimum. Other optimization algorithms might achieve better results for the *fixed-layout problem* as well as for the *free-layout problem*.

2. **Incomplete recordings:** Despite the use of three depth sensors, in some situations it occurred that either the OR lights or the arms of an OR light partially blocked the view to the OR area for all three depth sensors. For these frames, our $brightness(L, h_i)$ function may have returned higher values than expected. However, since our fitness function returns the minimum brightness of all frames, it can be assumed that such frames also tend to be considered less in the optimization due to their higher brightness.

3. **Behavior of the surgeons:** In the surgeries we recorded, two conventional OR lights were used. It could be that the movement behavior of a surgeon changes when a new autonomous lighting systems is used. This could lead to different results regarding the arrangement as well as the minimum brightnesses.

4. **Limited generality:** All our recordings took place in one operating room only. We do not yet know what results we obtain in other operating rooms and hospitals, where different standards may apply with regard to positioning. In addition, we cannot make any statement about how useful optimization is for individual operation types or a certain set of operation types that take place in a specific operating room.

[‡]Available on https://cgvr.cs.uni-bremen.de/research/smartot/

While limitation 1 is a basic feasibility and cost-benefit consideration, limitations 2-4 can be solved by taking more surgery recordings once the SmartOT lighting system is in use. The new lighting system would eliminate the need for conventional OR lights, which partially blocked the view of the depth sensors and might also have affected the behavior of the surgeons. By recording more surgeries, surgery types could also be distinguished.

7. CONCLUSION

We presented a method to optimize the arrangement of light modules of new autonomous lighting systems using point cloud recordings. For optimization, we captured nine point cloud recordings of real open surgeries at PIUS Hospital, Oldenburg, Germany. We formulated two optimization problems and implemented a greedy optimization algorithm as well as two heuristic optimization algorithms (SADE and SGA). Using cross-validation, we compared the optimized light module arrangements with naïve arrangements regarding the minimum brightness reached at the sensor over all considered frames in the respective surgery. With the optimized arrangements, we achieved up to 41 % higher minimum brightness compared to the naïve arrangements (comparing arrangement G49 with Greedy (Grid)) with a comparable number of light modules.

Our results suggest that optimizing the initial light module positions of such lighting systems result in significantly higher minimum brightness throughout the surgical procedure, even when the operating room is used by different surgeons, different medical staff, and for different types of surgery. Currently, our results still contain some uncertainties, such as that the motion profile of the surgeons in recordings might change when new illumination systems are used instead of the manual OR lights. To eliminate such uncertainties, we might perform new surgery recordings and optimizations as soon as the SmartOT lighting system is available for use in real surgeries.

ACKNOWLEDGMENTS

We are very grateful to the Pius Hospital, Oldenburg, especially Verena Uslar, for making the depth recordings possible. In addition, we would like to thank the technicians for installing the depth sensors in the operating room. This work was partially funded by BMBF grant 13GW0264D.

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