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Enhanced Visualizations of Thermographic Data in Process Industry

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ABSTRACT

In this paper, we describe an improved method for visualization of thermographic data in the paper and pulp process industry. We present an application that allows process operators to freely choose how absolute temperatures and time varying changes of thermographic scans should be mapped to colors and/or 3D shapes. Of the possible combinations, we selected two different forms of 3D visualizations and an existing conventional 2D map visualization. We then evaluated these visualization forms with regard to their effectiveness in experimental field studies. The field tests were carried out to measure the operators' performance in early detection of insulation damages on lime kilns. The results we obtained from the study show that the two new forms of 3D visualization lead to a reduction of the detection times by about two-thirds and one-third, respectively, when compared to the conventional 2D map representation. Since lime kiln monitoring is based on the rather generic method of continuous thermographic imaging, we suggest that these results also hold for the control and surveillance of other processes.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Color, shading, shadowing, and texture, I.3.8 [Computer Graphics]: Applications, H.4.2[Information System]: Decision support.

1. Introduction

Pulp and paper fabrication is a capital-intensive industry and it is therefore essential to optimally utilize the various processes involved. One of these processes concerns the recycling of chemical by-products in the mill that are handled in closed circulation and, hereby, pass through a so-called lime kiln. The kiln is a slightly slanted, slowly rotating metal cylinder with a steel shell that is about 60 meters long. The inner walls have two layers of bricks: one is used for insulation and the other is used as a burn layer.

Process operators control the recycling procedure by monitoring and adjusting temperatures in the kiln in order to optimize the reclaiming process, guarantee safe operation of the process and to save energy. Inaccuracies in process control lead, in the first instance, to reduced utilization. In worse, yet common cases, damage to the kiln entails an entire process shut down, resulting in substantial production loss. Therefore, it is crucial that potential problems in the lime kiln are discovered at an early stage to prevent problems. Early detection of deviations means identification of significant patterns in the variation of temperatures across the kiln surface. Knowing the exact location and degree of thermal irregularities in the kiln are crucial for taking appropriate countermeasures.

A widely used method for surveillance of absolute temperature is thermography. In thermographic imaging, heat emanating from any equipment surface is measured contact-free with infrared cameras and is visualized in real-time as a photographic portrayal of the inspected surface. Thermographic investigations are used for diagnostic purposes in many industrial applications [VDKF89] [BCSM86] [All98] as well as in medicine [KAYB98] or even art-history [GBMV94]. The websites uppco.com, flir.com and biomedx.com/mammotherm provide other examples.

A problem with visual interpretation of thermographic images is that the dynamic range in the captured images is very high compared to the number of discernible intensity levels in many of the color scales used for visualization. For instance, the measuring range of commercially available IR cameras is between -20°C to +900°C at a resolution of 0,1 degrees. This means that many details in thermal variation may be lost if fixed color palettes are used. In the case of variable color scales, the user is forced to mentally follow changes in the parameters of the window and level settings which implies extra cognitive efforts by the human observer.

The purpose of the work presented in this paper is to improve existing monitoring methods used in the surveillance of lime kilns by applying three-dimensional computer graphics and new, task-specific color palettes. In particular, we are interested in improving the operator's capabilities for detecting rather localized and rapid changes in the temperatures of lime kilns. These changes are a typical effect of insulation defects and always lead to severe damage if not immediately counteracted.

We follow an explorative research approach whereby we provide arbitrary mappings of relevant data attributes to different types of visual representations which are then assessed by domain experts. Some of the research questions at hand are, e.g. if the traditional methods in use can be improved by new combinations of color and 3D shape and if 3D as a visual cue adds to the efficiency in surveillance of time-varying thermo-graphic data.

2. Related work

There is little to be found in the literature about formal evaluations or research directly aimed at the problem described in the previous section. Instead, there seems to be a large number of applications in practical use that apparently have been developed according to best practices. In this section, we therefore give a more detailed description of the current method of thermographic surveillance of the recycling process in the kiln and give reference to other research relevant to the field. At first glance, thermographic imaging in general appears to be a very trivial task in which a two dimensional scalar field (absolute temperature values) is visualized. As is the case in conventional digital imaging, in thermography infrared data is presented to the user as a two-dimensional intensity image, whereby, in the most common case, temperature values are mapped to one color per pixel by means of some color mapping function i.e. a color scale. This color mapping technique is very generic and can be found in a variety of other imaging applications such as oceanography [NMGA*96], remote sensing [ShCa96] and geographically referenced data [EBHP98], just to mention a few examples.

3. Thermography in lime kiln surveillance

Lime kiln surveillance is facilitated through a high-resolution infrared line scanner that scans the entire surface of the kiln as it is rotating. A full scan of the entire kiln shell is, therefore, accomplished at an acquisition rate of $1/40s^{-1}$. The resulting image matrix is 123 columns by 512 rows and typically contains temperature values in the range of 50 to 450 degrees Celsius. Figure 1 shows a visualization application that is used daily for lime kiln surveillance.

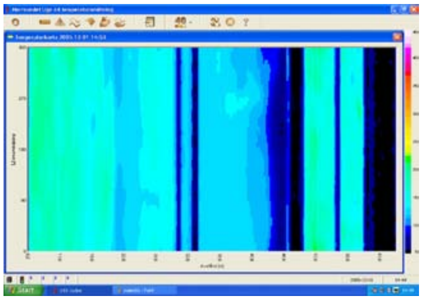

Figure 1: *Existing thermographic visualization.*

Most of the screen is dedicated to the 2D pseudo-color representation of the thermal image whereby, in this case, a fixed color palette (evident on the right hand side) is used in order to mediate the relevant information. The chosen color map is fixed in this particular application which, in general, allows for learning how colors translate to temperatures. It stretches over many different hues and, therefore, provides quite much chromatic variation and, hence, visual contrast (see also Figure 2). However, as is the case for many other similar palettes, e.g. the rainbow-palette [War88] [RoTr98], it is difficult to comprehend this color scale as an ordered value scale [War04]. Consequently, it is not really suitable for reading values and judging relationships but rather supports recognition of local variations in the 2D temperature distribution image [LiBa04] [RoTr98].

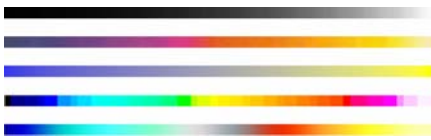

Figure 2: *Different color scales (Grey-scale, Extended Heated-Iron scale, Double-ended Blue-Yellow-scale, Presently used scale of Norrsundet, M3-scale). See also color plate.*

In applications such as thermography with a value scale of several hundred steps, reading absolute temperatures from a pseudo-color image is a very imprecise task. Therefore, an interactive querying cursor is used to retrieve precise temperature values from the image.

One of the operators' primary tasks is to monitor current temperature distributions across the kiln shell and to draw conclusions on bonded deposits on the interior wall of the lime kiln. The interpretation of the kiln's state of operation from the temperature distribution is not simply a matter of pure image analysis. Instead, it requires a lot of expert knowledge about the current composition of the by-products to be recycled, the current exterior temperature conditions, fuel-composition of the burner, the history of the recycling process during the past few days or weeks and much more domain knowledge. Therefore, this surveillance is preferably done by the human expert rather than by automated procedures.

Another task of the operators is early detection of irregular patterns of temperature distributions that can occur at varying rates over time, depending on the cause. This task also requires a lot of domain knowledge and is, therefore, not fully automated. The detection of time variations in the temperature requires differential assessment between any two given points in time. The existing application supports this by explicitly setting a reference infrared image in a history with which the current thermal image can be visually compared. To that end, the visualization works, as mentioned above, with fixed color palettes providing a constant base upon which visual comparisons may be performed.

Apart from the aforementioned benefits of fixed color scales, there is, however, one major drawback. Under normal conditions in the recycling process, temperatures in the lime kiln only reach levels that are in the lower third of the used color scale where there are only nuances of blue and cyan apparent. This problem is explicitly stated by the process operators, who usually see a relatively low-intensity and low-contrast image upon which to base their reasoning.

4. Visual mappings of temperature

In our discussions with the domain experts and users of the existing visualization system, we found that not only temperature but also the rate of change in temperature is a most important parameter that must be continuously monitored along with the current absolute temperature. So, the nature of the data is actually of the type of a two-dimensional two-component vector field. The existing visualization gives poor support to the extraction of both the current temperature and temporal changes in temperature by simply flipping two images and visually comparing them. Another weak point that we identified was the choice of the color scale which we tried to improve using theory and experimental findings in the literature.

4.1. Height field and cylindrical mapping

Despite the fact that the original data measured with the infrared scanner represents scalar data, let us for the purpose of visualization consider the data of interest as a two-dimensional field of two-component vectors at a given time t as:

$$T_{i,k}^{t} = \begin{pmatrix} \theta \\ \Delta\theta \end{pmatrix}_{i,k}^{t} = \begin{pmatrix} \theta \\ \theta \end{pmatrix}_{i,k}^{t} - \begin{pmatrix} 0 \\ \theta \end{pmatrix}_{i,k}^{t-\Delta t} \quad (1)$$

t and k are the row and column indexes of the thermographic image matrix. Here, Δt is a user adjustable time interval for reference measurements in the past to compare with the current temperature measurements. It is obviously difficult to visualize both vector components simultaneously with colors in a 2D map representation and the relatively high resolution of the thermal image precludes other visual coding schemes such as 2D glyphs or texture patterns. We therefore extend the visualization into the third dimension. The most obvious form of a 3D representation is by drawing a height field, whereby one vector component of the temperature field from (1) modulates the elevation in the height field and the other component is represented as a color such that:

$$x = c_i \cdot i \quad (2)$$

$$y = c_k \cdot k \quad (3)$$

$$z = o + s \cdot \Delta\theta_{i,k}^{t} \text{ and } C_{x,y,z}^{t} = \theta_{i,k}^{t} \quad (4)$$

or

$$z = o + s \cdot \theta_{i,k}^{t} \text{ and } C_{x,y,z}^{t} = \Delta\theta_{i,k}^{t} \quad (5)$$

c_i , c_k, s are scaling variables and o is the offset parameter of the linear transformation.

In the mappings denoted in (4) color C is used to express absolute temperature at a given time stamp t, whereas the derivative of the temperature over a given interval Δt is mapped linearly upon the height value z in the height field representation, or vice versa in (5). An example of a height field mapping according to (5) is shown in Figure 4 (bottom), where absolute temperature is mapped upon elevation in the height field. The actual emphasis of the temporal change of temperature in this visualization can be controlled by the scaling variable of the linear transformation. The distinctiveness of the height map approach for depicting small variations must still not be overestimated. In particular, when rendering the height map in a solid shading mode, small spatial deviations in the map are difficult to perceive when they are surrounded by surface regions with similar colors, i.e. temperatures. Then it is only on the borders and the silhouette of the height field where details can be seen quickly; or by introducing motion into the visualization.

This observation led us to the idea of a different visualization which maps the original data upon a cylinder as follows:

$$x = c_i \cdot i \quad (6)$$

$$y = r \cdot \sin(c_k \cdot k) \tag{7}$$

$$z = r \cdot \cos(c_k \cdot k) \tag{8}$$

With

$$r = o + s \cdot \Delta\theta_{i,k}^t \quad \text{or} \quad r = o + s \cdot \theta_{i,k}^t \tag{9}$$

Then

$$C_{x,y,z}^t = \theta_{i,k}^t \quad \text{or} \quad C_{x,y,z}^t = \Delta\theta_{i,k}^t \tag{10}$$

This cylindrical visualization is then automatically rotated about the cylinder axis with the angular rate of 10 revolutions per minute. We presume two benefits of this visualization. First of all, the visualization of the data is equivalent in shape with the surface from which the data is collected. It is intuitive for the operators to understand this kind of representation and the rotation of the cylindrical map is also equivalent with what they are used to seeing in reality. Depending on the way in which absolute temperature is mapped upon the radius, the apparent deformation of the cylinder surface actually corresponds to the structure of the bonded deposits inside the walls of the lime kiln.

A second advantage is that the cylindrical shape presents two clearly delineated and straight silhouette edges. When the cylindrical visualization is revolving, spatial deviations in the surface shift through the silhouettes where they are clearly evident and where they can be quantitatively compared along the the assumed normal line of the silhouette edge.

For each of the two 3D visual mappings there exist four combinations in which the data can be mapped upon spatial shape and color. Together with the traditional 2D color-map visualization, we get 10 different configurations for the visualization of current temperature and derivatives of temperature over time. Table 1 summarizes these combinations. We developed an integrated visualization application that allows the operators to choose these mappings arbitrarily even though not all of the possible combinations occur as expressive visualizations. In table 1, those visualizations are marked with gray which we, in consensus with the process operators, considered interesting for further empirical investigation.

4.2. Color mapping

In the area of thermograpy there are two commonly used color scales: the Rainbow- and the Heated Iron scale. The Rainbow scale is a hue-based scale traversing the color solid along a path from black to white through all the hues of the rainbow with a variation in luminance. The Heated Iron scale is based on the metaphor of metal being heated. In our study we used the Extended Heated Iron scale with colors black, magenta, red, orange, yellow and white (see Figure 2) which has a luminance increase along the scale, similar to the grey-scale, see Figure 3.

Visualization	Color	Shape
2D map	θ	-
2D map	Δθ	-
3D field	θ	θ
3D field	θ	Δθ
3D field	Δθ	θ
3D field	Δθ	Δθ
3D cylinder	θ	θ
3D cylinder	θ	Δθ
3D cylinder	Δθ	θ
3D cylinder	Δθ	Δθ

Table 1: *Scheme over possible mappings.*

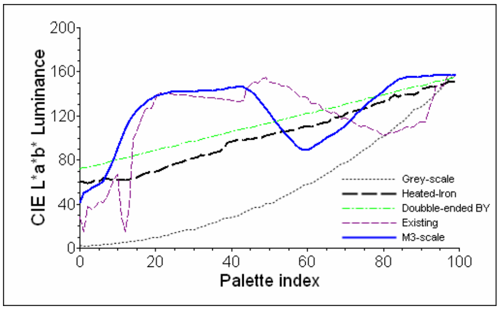

Figure 3: *CIE L*a*b* approx luminance curves.*

The color scale currently in use is segmented with no variation within the different bands. Instead, we selected the Extended Heated Iron scale for the mapping of absolute temperature in the application, see Figure 2. The motivation for this choice is the almost linear and continuous increase of luminance which signifies a good interpretation of interval data [Lev96] [LiBa04] [Rhe00] and [War04]. Color distance and color category are factors that have to be kept in mind when selecting suitable colors for a scale [Hea96] [HeEn99]. In our application, temperature data can be considered as ratio data. I.e. we have continuous temperature scans with a "normal" temperature level and two critical divergences. Hence, a diverging scale ought to be suitable. A double-ended scale would also be appropriate given the fact that the emphasis is on the critical values [Rhe00], [Bre99] and [War04]. However, we also need to identify increasing or decreasing trends. We therefore introduce the Min-Mean-Max scale, M3, to facilitate the discrimination of $\Delta\theta$ in the lime kiln. In the M3 scale, we advocate a three section luminance based scale for the visualization of $\Delta\theta$. The M3 scale is composed of a centered, grayscale for normal values in the data and two separate color bands attached to either side of this grey scale. The min-band is for low temperatures and the max-band for high temperatures. Colors within these bands are chosen on a metaphor for cold and warm. The min-band stretches from blue over cyan to green for values below the normal temperature. The max-band stretches from red across orange to yellow, for values above the normal (see Figure 2). As can be seen in Figure 3, the M3 scale has significant variation in the luminance curve. Rather than following a straight luminance profile or using two opponent colors as recommended in earlier research [Rhe00][War04], we aim at steep deviations of luminance in the region of the mean-band in order to support easy discrimination of small deviations from normal when shell overheating occurs. In the min-band, we use a higher luminance value in the beginning of the scale with decreasing luminance towards the end. The reason for this is the fact that, in the cooling process of the lime kiln, the critical stage is not reached for a relatively long period.

5. Field study

In this section, we describe how we evaluated some of the possible visualizations described in section 4. Throughout the development of the thermographic surveillance application, the operators were very frequently involved in the design process. Therefore, the motivation to volunteer for practical field studies was very high. Due to the very time demanding nature of these types of experiments and to the large number of possible combinations (see table 1), we did not aim in this early stage for a full factorial analysis of the independent variables that characterize the visual mapping.

Instead, the objective of this first field study was to evaluate the effectiveness of the two most preferred visualizations and to compare them with a 2D color map representation of absolute temperature. These evaluations should be performed under realistic conditions in the actual working environment of the process operators.

Due to the limitations of the color scale presently in use and in order to better compare the traditional 2D map method with our new visualizations, we applied the same color scale for absolute temperatures for both the 3D and 2D visualization forms. For representation of absolute temperature, we chose the Extended Heated Iron scale shown in Figure 2. To avoid interference with the in-house systems installations in the operator's room, we decided to add another stand-alone computer and monitor for surveillance of a new, though virtual, lime kiln. This virtual lime kiln was simulated by replaying thermographic data records that were logged from the real process several months prior to the experiment. The test application retrieved thermographic image frames at realistic rates and simulated irregular thermographic patterns which are typical for the most rapidly occurring damages such as sudden insulation defects. To that end, we went through historic data records and identified the shape of typical irregularities which we stored as digital image templates. Supported by the experts' assertions, we analyzed their typical temporal course over time. From that, we heuristically modeled localized overheating of the kiln shell by fitting a quasi-exponential function that approximates relative increases in temperature over time. The simulated temperature increase was applied to the data by using the templates for typical defect patterns. Figure 4 shows a simulated defect in the three different visualization forms.

From discussions with the process operators it became clear that these critical events of sudden shell overheating occur rapidly. With insulation defects, the temperatures can increase locally by 350 degrees Celsius within only five to seven minutes which requires very early detection and countermeasures. Therefore, in our study, we measure the efficiency of a visualization by measuring the operator's response time to detect and report a simulated defect for each visualization under investigation.

Two working teams (labeled "Team B" and "Team F") were allotted three afternoon shifts each, where the teams had to monitor the virtual lime kiln. During a shift, only one of the selected visualization forms (see table 1) was used for a period of four hours. During this time span, six accidents where sporadically simulated at randomized times and at randomized positions on the kiln surface.

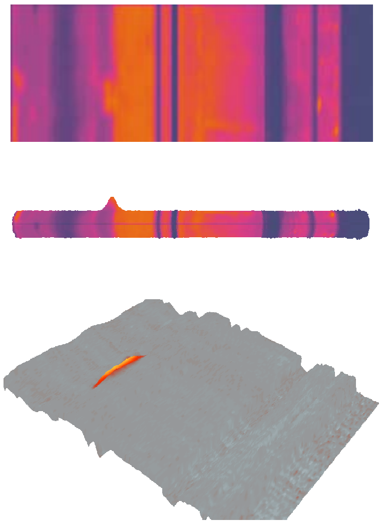

Figure 4: *Examples of the three different visual mappings (Map, Cylinder and Field).*

Random times and positions where calculated beforehand and then used for both teams. Given the rapid progression of temperature increase and the relative slow update rate of the thermographic scan (1/40 sec^{-1}), there are only a few distinct frames in the visualization to represent the course of the defect. As soon as an operator reports a defect, the time is registered and the operator is required to indicate the position of the assumed defect using the mouse cursor. In this way, we can identify if a registered defect was encountered correctly or erroneously.

For each of the two teams, three visualizations where tested, whereby six defects (i.e. detection times) where registered, resulting in a total of 36 measurements.

6. Results

The result from this applied research is twofold. First and most important to the actual end users, there is a new visualization application for process operators to monitor the recycling processes in the lime kiln based on continuous infrared surface scanning. Since process operators participated in the design step of this application, we are rather confident that this application meets the requirements for practical use and that it surpasses the performance of the existing application. Figure 5 shows another screenshot of the final system. At the time of writing this paper, the application is about to be integrated into the real operators working environment by interfacing it with the dataflow of the existing process monitoring system.

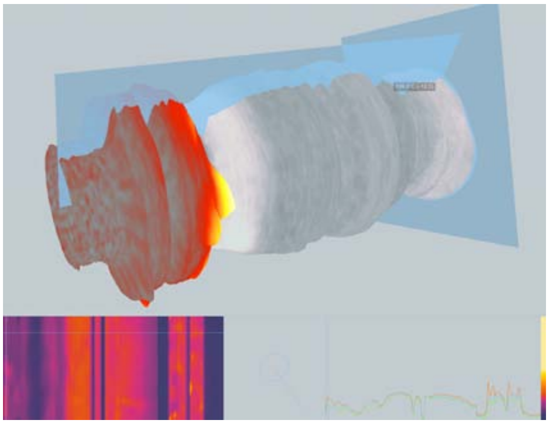

Figure 5: ***Example of a visual mapping, where θ is mapped upon the cylinder radius while $\Delta\theta$ is color mapped using the M3 scale.*** *See also color plate.*

In addition, we gathered interesting data from our field study which have relevance for the visualization research community and researchers in process control and alarm handling. From the experimental trial with the simulated lime kiln, we observed detection times of the two working teams for the three different visualization forms according to table 2. Values presented in the table are the mean values of the six observations from each trial. The measured detection times show that the 3D height field visualization with color coding of temperature differences and elevation mapping of absolute temperature reduces average detection times for both working crews by 63% based on the times for the conventional 2D color map technique. For the 3D cylindrical mapping with color coding of absolute temperature and displacement mapping of differential temperature, this reduction is 35%. We informally collected other results in the form of subjective feedback from the operators which we recapitulate in the discussion section.

	Map	**Field**	**Cylinder**
Team B	167	59	83
Team F	142	54	117
Average	154	57	100

Table 2: *Response times of the two teams for the three conditions. Times are measured in seconds.*

7. Discussion

In regard to our initial research question, we observe that the combined visualization of both absolute temperature and temperature difference in form of 3D visualizations clearly reduces the detection times for defects compared to the time required for conventional 2D color map representation of absolute temperature. This is an evident result and we let these figures stand for themselves in spite of statistical significant interactions between all conditions, which can be shown by pair-wise t-testing of the 12 observations. The reason for not drawing any statistical analyses on these results is that there are many factors in our first field study that affect interpretation of the results. We only looked at two different working teams that participated in the study. Also, even though we collected a total of 12 detection times (six in each group) for each visualization condition, we still only have a very small test population upon which to base our conclusions. During each four-hour experimental session, we registered the detection performance of six incidents as the result of the entire working team's combined efforts. We have no deeper insight as to how individuals in the team delegated tasks and what other events during process control affected the users' attention.

What is interesting to note is that the 3D cylindrical mapping of the data leads to longer detection times when compared to the 3D field visualization. This may seem to falsify our previous assumptions that we had with regard to improved recognition of 3D structure in the silhouette of the cylinder. It is still difficult at this point to say if this result is due to the cylindrical mapping or due to the different use of color mapping that characterizes these two 3D visualizations.

If results are interpreted from the perspective of the users in terms of total average detection times, it can be seen that the 3D field view leads to a decrease from 154 sec to 57 sec which gives an extra of 97 sec of valuable time for making decisions and taking counteractions. For the 3D cylindrical visualization, this extra time margin is 54 sec.

An explanation that remains to be delivered concerns the factors that have contributed to the obviously improved detection times for the 3D visualizations. Did the introduction of the M3-color scale for encoding differential temperatures cause the improvement or was it the spatial coding of the absolute temperature? As mentioned before, a full factorial analysis would have required testing all 10 combinations from table 1 with a much larger population. It is obvious that these types of experiments cannot be performed in field studies. Instead, they would require much larger studies under controlled conditions.

At this point in our applied research, however, the relative value of improved 3D visualizations of time varying thermographic data in practical use is the foremost objective of our studies. In that sense, our field study gives very clear indications that speak positively for both forms of 3D visualizations that were investigated.

The comments of the process operators after participating in the study also support the observed measurements. They experienced that the cylindrical visualization was easy to interpret as it mapped the data in an intuitive way. However, the best discrimination was experienced with the height field interface.

We constructed our new M3 scale with the intention of increasing the discrimination of temperature changes in the lime kiln supervision. By using variations in luminance, our goal was to put emphasis on the most critical events: shell overheating. The 3D field visualization was the only presentation form that used mapping of differential temperature upon the M3 scale and it showed the best performance. It appears likely that this could be due to the M3 scale rather than the 3D shape even if we have no statistical evidence for this at the moment. Also, according to the comments of the process operators, the use of the M3 scale was considered an improvement even for conventional 2D map visualization for temperature variations.

The results presented here were acquired in the context of the pulp and paper industry and, more specifically, in surveillance of lime kilns. Yet, we presume that they are not only confined to this particular field of application. Visual interpretation of sequences of thermographic images is a method that follows the same principal procedures and is generally required for diagnostic procedures, surveying tasks and monitoring in many other fields. Common to all these tasks is the interpretation of the current situation, distinctive patterns and temporal deviations in a distribution of temperatures. What renders different applications specific are the rate of change in the data, the levels of temperatures and the specific patterns that require attention. We estimate that this only affects absolute levels of user-performance in between various applications but not the relative difference between 2D visualization and the proposed 3D visualizations in any of the given task domains.

8. Conclusion and future work

In this paper, we have presented a new visualization application for surveillance of recycling processes in lime kilns. As an application-driven tool, it is aimed to enhance the operators' ability to visually analyze and assess the data delivered by the process control system. In this regard, the tool introduces new means to visually map time varying thermographic data. As a scientific tool, this application allowed us to assess the value of two new 3D visualizations in practical use. To that end, we performed field studies in the real working environment of process operators by simulating a virtual lime kiln allowing us to introduce process-irregularities in a controlled manner. From the observations in this field study, we can conclude that, in the practical working context, the two forms of 3D visualizations lead to clearly improved detection times for irregularities when compared to the conventional 2D form of visualization currently in use. Informal feedback from the process operators expressed deep satisfaction over improved possibilities to visually analyze the data. This is not only due to the flexibility of mapping data to visual forms but also owing to e.g. the improved possibilities for changing time intervals for differential analyses. At the writing time of this report, our visual surveillance application is being fully integrated into the process control system at the paper and pulp mill of Stora Enso in Norrsundet where it is now undergoing a six-month on-site evaluation in parallel with the existing visual monitoring software.

From a visualization research point of view, this initial field study gave rise to a number of new research questions that form the basis for new controlled observation studies. For instance, we have a study planned, that investigates the effect of different color palettes compared to the use of 3D shape in visualization of thermographic data.

9. Acknowledgment

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References

[All98] ALLRED L. G., Identification of age degradation in EPROM chips using infrared thermography, Thermosense XX, SPIE Proceedings Vol. 3361, (Apr98) pp35-39.

[BCSM86] BELICJENKO A. I., CHEPA V. V., SAAPIN V. I., MIKALOVSKAYA O. M., System for monitoring and controlling the lime level in the shaft coolers of rotary kilns, Metallurgist, 30:6 (June86) pp 222-223.

[Bre99] BREWER C., Color guidelines for data representation, proceedings of the section on statistical graphics, American Statistical Association, Alexandria VA, 1999, pp 55-60.

[EBHP98] Mac EACHREN A. M., BOSCOE F. P., PICKLE L., Geographic Visualization: Designing Manipulable Maps for Exploring Temporally Varying Georeferenced Statistics, IEEE, Proceedings of Information Visualization ´98, pp. 87-94 (1998).

GBMV94] GRINZATO E., BISON P., MARINETTI S., VAVILOV V., Nondestructive valuation of delaminations in fresco plaster using transient infrared thermography, Research in Nondestructive Evaluation, 5:4 (Dec 94) pp 257-274.

[HEEN99] HEALEY C. G. and ENNS J. T. Large datasets at a glance: Combining textures and colors in scientific visualization. *IEEE Transactions on Visualization and Computer Graphics 5*, 2 (1999), 145–167.

[Hel96] HEALEY C. G. Choosing effective colors for data visualization. *Proceedings Visualization '96* (San Francisco, California, 1996), pp. 263–270.

[KAYB98] KEVSERLINGK J. R., AHLGREN P. D., YU E., BELLIVEAU N., Infrared imaging of the breast: Initial reappraisal using high-resolution digital technology in 100 successive cases of Stage I and II breast cancer, The Breast Journal 1998:4 PP.245-251.

[Lev96] LEVKOWITZ H., Perceptual steps along color scales, *International Journal of Imaging System and Technology* , 7:97-101, 1996.

[LiBa04] LIGHT A., BARTLEIN P. J., The end of the rainbow? Color schemes for improved data graphics, Eos, vol 85, No 40, (Oct 2004).

[NMGA*96] NATIONS S., MOORHEAD R., GAITHER K., AUKSTAKALNIS S., VICKERY R., COUVILLION Jr W. C., FOX D. N., FLYNN P., WALLCRAFT A., HOGAN P., SMESTAD O. M., Interactive visualization of ocean circulation models, *VIS '96: Proceedings of the 7th conference on Visualization '96, (*1996)pp 429--ff.

[Rhe00] RHEINGANS P., Task-based color scale design, Workshop 3D Visualization for Data Exploration and Decision Making, ed Oliwe E. R., Proc of SPIE Vol 3905, 2000.

[RoTr98] ROGOWITZ B. E., TREINISH L. A., Data visualisation: The end of the rainbow, *IEEE Spectrum, 35, n. 12 (Dec1998) pp. 52-59.*

[ShCa96] SHIRI S., CAVALLO J. M., Remote Sensing and Environmental Data Visualization in GLOBE Program: Automated and On-Demand Visualization Using IBM Data Explorer, *Proc of the 1996 IBM Visualization Data Explorer Symposium* (Oct 96), IBM OpenDX workshop, San Francisco 1996.

[VDKF89] VASILl"ev L. L., DRAGUN S. V., KONEV S.V., FILATOV S. A., Methods of computational thermography in the nondestructive testing of the quality of heat pipes and heat exchange devices based on them, Journal of Engineering Phyics and Thermophysics, 57: 3 (Sept 89) pp 1068-1073.

[War88] WARE C., Color sequences for univariate maps: Theory, experiments, and principles. *IEEE Computer Graphics & Applications 8*, 5 (1988), 41–49.

[War04] WARE C., Information Visualization, perception for design, Morgan Kaufman Publisher, SanFrancisco, CA, USA, Academic press, 2004.