Popular Summary

Humankind's wish to be able to record and film events has probably existed for millennia, however, it wasn't until the late 19th century when this was made possible for the first time. At that point one had for a long time admired the gracious way horses galloped, but a single question was under heated debate: does a horse completely leave the ground when it gallops? It was the industrialist, horse enthusiast and ex-governor of California, Leland Stanford, who decided to solve this debate, not only out of curiosity but legend has it that he had a $25000 bet placed on his theories[1]. So he employed the photographer Eadward Muybridge, and in 1878 they were able to capture a four image movie of the horse, Sallie Gardner, and jockey, Gilbert Domm, finally showing that horses leave the ground as they gallop (see the figure). The general public had a hard time accepting these findings as they found the images of the horse's movements to be quite ungracious. Furthermore, many even questioned the reason to interfere with God's created beauty of the world. Eadward Muybridge went on to publish an encyclopaedia type book about Animal Locomotion where animal and human subjects[2] were filmed with his tripwire based shuttering contraption.

This technological feat opened up for the possibility to quench humans' innate curiosity of seeing natural events in slow motion, and today, the ability for slow motion capture or *high-speed videography* exists, to a certain degree, within everybody's pockets. However, as is always the case in science, we feel the need to do better and in this case that would mean to film faster. Indeed, what if we could film fast enough for nothing to happen, such that even light, which travels at the fastest speed of which anything can travel, is stopped in its tracks? Surely that would be the end of the line? This is where the work presented within this thesis comes into play, as during my PhD I have worked on developing techniques for attaining video speeds that are capable of "stopping light". I then worked on applying them to various natural events, such as plasmas, where things go at such speeds that one does not have a choice but to film with a "stopping light" type of technique (an example video taken by us in Lund is shown in the lower panel of the figure).

The title of this thesis, **Structured Light for Ultrafast Videography** can be divided into two parts: structured light and ultrafast videography, where the intertwining of these two concepts forms the basis of the discussions within this thesis.

Ultrafast Videography entails the filming of ultrafast phenomena. And no, I am not

[1]There is no evidence to this legend however I always like to include it because he actually ended up spending about $50000 in total, spending more than he bet. For context $50000 in 1880 is worth $1 500 000 in 2024, i.e., about 15 years' worth of what I cost my supervisor as a PhD student per year.

[2]It is debated if the human subjects were really filmed out of scientific curiosity as men were filmed performing physical tasks while women were filmed e.g., "opening a parasol and turning around" in revealing clothing. Whatever it was, the nudeness did stir up quite a bit of controversy!

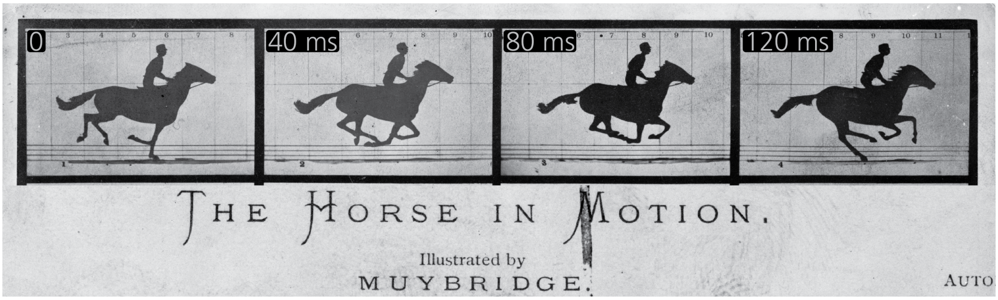
joking, the scientific term is indeed ultrafast. This type of event, (such as the rotation of molecules, or the creation of plasma light channels called filaments) occur on timescales faster than 1 picosecond, i.e., 0.000000000001 seconds (that's 11 zeros after the decimal point). Therefore in order to capture such events we need to film at corresponding speeds i.e., above 1 000 000 000 000 frames per second[3]. This is so fast that if one compares the necessary shutter time of the camera to one second, that would be equivalent to the time comparison between a day and the age of the universe!

These shutter speeds are so fast that the speed of electrons (the carriers of information in cameras) within the electronic circuitry of cameras is simply too slow for this approach to be useful. Therefore, one needs to use light instead, in particular ultrashort laser pulses. In this part of the title, **Structured Light**, light pulses are created and manipulated such that they (1) illuminate the event like a stroboscope would, but at an ultrafast speed and (2) they are structured such that they have unique striped patterns imprinted onto them. As will be shown within this thesis, together these two manipulations are enough to be able to open up the realm of ultrafast videography.

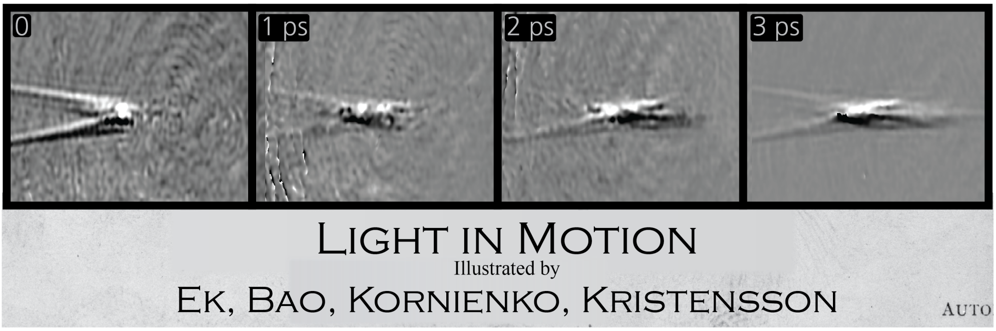
Within this thesis work, paid by you the taxpaying reader, I firstly delve into the magical world of optics, lasers, imaging and videography and try to compare all these technologies to what we have closest to us, our eyes and vision (I would encourage even the non-physicist to read this). Then I talk in depth about existing technologies and their inner workings, such as lasers systems and high-speed camera systems. I follow with a discussion in the necessary mathematics before coming out the other end and showing the reader that during my time as a PhD student we have been able to develop, not only niche ultrafast videography systems, but also a high-speed video system that is commercially viable. With that, I hope you had and will have a good read.

[3]For reference, standard movies are filmed and projected on your television or computer screen at 24 or 144 frames per second respectively.

1877: 25
frames per second / bilder per sekund / images par seconde



2024: 1 000 000 000 000
frames per secomd / bilder per sekund / images par seconde



Eng: From the horse to light in motion. What a long way videography has come, eleven orders of magnitude, i.e., 10^{11}, faster!

Swe: Från hästan till ljus i rörelse. Vad långt filmning har kommit, elva storleksordningar snabbare, dvs 10^{11} gånger snabbare!

Fr: Des chevaux à la lumière en mouvement. Quel chemin long la vidéographie a parcouru, onze ordres de grandeur, c'est-à-dire 10^{11} fois plus rapide!