Self-optimized Side-emitting Fiber-based Optical Camera Communication System for Sensor Data Transmission

Electronics and Communications

Czech Technical University

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Samo-optimalizovanĬ syst®m pro pŝenos senzorickĬch dat za vyuģit² stranovĕ-vyzaŝuj²c²ch optickĬch vl§ken a komunikace pomoc² optick® kamery

N§zev bakal§ŝsk® pr§ce anglicky:ث

Self-optimized Side-emitting Fiber-based Optical Camera Communication System for Sensor Data Transmission

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ZADĆNĈ BAKALĆřSK£ PRĆCE

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Pokyny pro vypracov§n²:ث

C²lem bakal§ŝsk® pr§ce bude teoretick§ reġerġe, rozbor a n§vrh praktick®ho ŝeġen² v¦etnŊ experiment§ln²hoث
ovŊŝen² pŝenosu senzorickĪch dat (ze senzoru teploty) pŝes komunika¦n² spoj tvoŝenĪm LED zdrojem nav§zanĪmث
do stranovŊ-vyzaŝuj²c²ho optick®ho vl§kna dohromady tvoŝ²c²ch vys²lac² ¦§st a optick® kamery jako pŝij²ma¦e.ث
Pr§ce se zamŊŝ² pŝedevġ²m na pŝevod senzorickĪch dat do vhodn®ho form§tu pro pŝenos navrġenĪm optickĪmث
syst®mem a d§le na zpracov§n² obrazu stranovŊ-vyzaŝuj²c²ho vl§kna na vĪstupu kamery. Propojen² senzorick®ث
¦§sti a optick®ho vys²la¦e bude realizov§no pomoci mikrokontroleru. V r§mci pr§ce probŊhne optimalizaceث
prvkŢ pŝenosov®ho syst®mu (v²ce druhŢ stranovŊ-vyzaŝuj²c²ch vl§ken, optick® kamery, objektivy, atd.). Budeث
analyzov§n vliv zakŝiven² stranovŊ-vyzaŝuj²c²ho optick®ho vl§kna a rovnŊġ bude uvaġov§n i pohybuj²c² seث
vys²la¦ (stranovŊ-vyzaŝuj²c² optick® vl§kno napŝ. na odŊvu).ث
V r§mci projektu ŝeġte tyto ¼lohy:ث
1) Vypracujte reġerġi na t®matiku komunikace pomoc² optick® kamery (optical camera communication) v obecn®ث
rovinŊ a n§slednŊ v souvislosti se stranovŊ vyzaŝuj²c²mi optickĪmi vl§kny (side-emitting optical fibers).ث
2) Diskutujte moġnosti zpracov§n² obrazovĪch dat z hlediska optick® kamery.ث
3) NavrhnŊte parametry komunika¦n²ho ŝetŊzce pro spolehlivou komunikaci na vzd§lenost do 4 metrŢ (indoorث
scenario) v¦etnŊ blokov®ho uspoŝ§d§n².ث
4) Realizujte experiment§ln² zapojen².ث
5) Zpracujte z²skan§ data z bodu 5) na z§kladŊ V§mi navrġen® metody zpracov§n² obrazovĪch dat pro rovnĪث
¼sek stranovŊ-vyzaŝuj²c²ho vl§kna.ث
6) ProveŅte optimalizaci nutnĪch prvkŢ komunika¦n²ho ŝetŊzce.ث
7) ZamŊŝte se na funkci auto-optimalizace komunika¦n²ho ŝetŊzce.ث
8) Analyzujte metody sledov§n² pohybuj²c²ho se vys²la¦e (optick® vl§kno) a vliv zakŝiven² stranovŊ-vyzaŝuj²c²hoث
vl§kna na kvalitu pŝenosu dat.ث
9) ShrŔte dosaġen® poznatky a vyhodnošte vĪsledky.ث
VĪstupem bakal§ŝsk® pr§ce bude n§vrh, analĪza a optimalizace komunika¦n²ho syst®mu pro pŝenosث
senzorickĪch dat za vyuġit² stranovŊ-vyzaŝuj²c²ch optickĪch vl§ken a komunikace pomoc² optick® kamery.ث
Syst®m bude schopen automatick®ho nalezen² optim§ln² konfigurace s pŝ²padnou moġnost² sledov§n²/predikceث
tzv. Region of Interest.ث

Seznam doporu¦en® literatury:ث

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DECLARATION

I, the undersigned

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declare that I have elaborated the bachelor's thesis entitled

Self-optimized Side-emitting Fiber-based Optical Camera Communication System for Sensor Data Transmission

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I declare that I used artificial intelligence tools during the preparation and writing of this thesis. I verified the generated content. I hereby confirm that I am aware of the fact that I am fully responsible for the contents of the thesis.

In Prague on 21.05.2025

Jakub Formánek
....
student's signature

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Abstract

This thesis presents the design, implementation, and evaluation of a real-time Optical Camera Communication (OCC) system using a side-emitting optical fiber as a distributed light transmitter for sensor-data links. A microcontroller samples a temperature sensor, applies Manchester coding, and drives a high-power LED coupled into the side-emitting fiber, while a rolling-shutter camera with a C++/OpenCV pipeline automatically tracks the fiber's Region of Interest (ROI), demodulates stripe patterns in real time, and recovers the transmitted data. Real-time decoding was maintained up to 100 cm, in live tests at 60 cm using temperature-sensor data, 20,000 frames ($\approx$360 kbit) captured at $\approx$40 fps yielded 722 bit/s throughput, a Bit Error Rate (BER) of 6.25×10^{-5}, and a packet-success rate of 99.7 %. The system was also tested under bent and moving fiber conditions, where BER rose to 6×10^{-2} for bent fibers, while still reliably detecting the ROI, and to 1×10^{-3} for moving fibers. This low-cost, modular platform demonstrates reliable real-time OCC for Internet of Things (IoT), wearable, and ambient-lighting applications, and lays the groundwork for future enhancements in OCC, secure encoding, and fabric integration.

Keywords

Optical Camera Communication; Side-Emitting Fiber; Manchester Coding; Rolling-Shutter Demodulation; Real-Time Sensor Data

Abstrakt

Tato prace predstavuje navrh, implementaci a vyhodnocen systemu komunikace optickou kamerou (OCC) v realnem case vyuzvajcho stranove vyzarujc opticke vlakno jako distribuovany zdroj svetla pro prenos dat ze senzoru. Mikrokontroler snma udaje z teplotnho senzoru, aplikuje Manchester kodovan a rd LED diodu pripojenou k vlaknu, zatmco kamera s rolling-shutter senzorem a C++/OpenCV pipeline automaticky sleduje oblast zajmu, v realnem case demoduluje prouzkove vzory a obnovuje prenasena data. Komunikace optickou kamerou v realnem case byla zachovana az do 100 cm, pri testech na 60 cm s daty z teplotnho senzoru bylo porzeno 20 000 snmku (360 kbit) pri 40 fps, coz vedlo k prenosove rychlosti 722 bit/s, bitove chybovosti 6;25 10^{5} a uspesnosti prenosu paketu 99,7 %. System byl rovnez testovan pri ohnut a pohybu vlakna, kdy se bitova chybovost zvysila na 6 10^{2} pro ohnut, pritom byla stale spolehlive detekovana oblast zajmu, a na 1 10^{3} pro pohyblive vlakno. Tato nzkonakladova, modularn platforma dokazuje spolehlivou realnou OCC pro internet vec (IoT), nositelna zarzen a ambientn osvetlen a tvor zaklad pro budouc vylepsen v oblasti komunikace optickou kamerou, zabezpeceneho kodovan a integrace do textili.

Kl ova slova

Komunikace optickou kamerou; Stranove vyzarujc vlakno; Manchester Coding; Rolling-shutter demodulace; Prenos senzorickych dat v realnem case

Acronyms

OWC Optical Wireless Communication

OCC Optical Camera Communication

VLC Visible Light Communication

OOK On-O Keying

ROI Region of Interest

MST Minimal Spanning Tree

BER Bit Error Rate

IoT Internet of Things

FEC Forward error correction

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Chapter 1

Introduction

Optical Camera Communication (OCC) has emerged as a promising branch of Optical Wireless Communication (OWC), leveraging widely available LED emitters and rolling shutter image sensors to create low cost, versatile data links. Side emitting optical fibers, which scatter light uniformly along their length, offer unique advantages for OCC, omnidirectional emission, mechanical flexibility, and seamless integration into ambient or wearable formats. To date, however, all demonstrations of OCC using side emitting optical fibers have relied on offline processing of captured images or video, limiting their applicability in real time scenarios.

This bachelor thesis presents the first real time OCC system employing a side-emitting optical fiber as the distributed light source. On the transmitter side, a microcontroller encodes sensor data with Manchester coding and drives a high-power LED coupled into the side-emitting optical fiber. On the receiver side, a Raspberry running a C++/OpenCV pipeline captures rolling shutter frames from a camera, locates the fiber's region of interest under static, bent, or oscillating conditions, and decodes the transmitted data in real time.

The objectives of this work are to design and implement a hardware interface for side-emitting optical fiber transmission, develop a robust real time image processing chain including automated Region of Interest (ROI) detection, characterize performance metrics such as bit error rate, validate packet rate and throughput across varying distances from 20 to 120 cm, fiber curvatures with radii of 212 mm and 392 mm and motion of 20 at 1 Hz, and demonstrate reliable real time transmission of live sensor data. By achieving these aims, this thesis establishes a practical foundation for further advancements in fiber based OCC for the Internet of Things (IoT), ambient lighting and wearable applications.

Chapter 2

State of the Art

Optical Camera Communication (OCC) represents a promising subset of Optical Wireless Communication (OWC), enabling data transmission using light-based source and standard optical camera as receiver. This technology employs existing LED infrastructure and commercially available camera modules, making it both cost-effective and easily to integrate into current lighting systems.

OCC has seen significant advancements in recent years, focusing on enhancing computational and spectral efficiency, increasing data rates. For example, in [1], a system was developed with six light channels consisting of two RGB LED diodes and a camera capable of capturing 60 frames per second (fps). This system achieved data rates of up to 10.8 kbps over a distance of 2 meters, with offline video processing performed in MATLAB.

In [2], OCC was tested with a moving receiver, achieving data rates of up to 4.08 kbps with lateral distances of 50 cm and 70 cm. The bit error rate (BER) was found to be proportional to the movement speed, which reached up to 100 cm/s. The image processing was performed offline using MATLAB.

In [3], an OCC system was demonstrated with net data rates of 1.92 kbit/s, 3.84 kbit/s, 5.76 kbit/s, and 7.68 kbit/s when using payload bit lengths of 32 bits, 64 bits, 96 bits, and 128 bits, respectively. BER of 10^{-6} was achieved for 32-bit and 64-bit payloads. The data were processed offline in MATLAB.

In [4], an OCC system utilizing side-emitting fiber achieved the forward-error-correction (FEC) limit for transmission up to 35 meters with a modulation frequency of 3.54 kHz using a 2 mm side-emitting fiber. For a 3 mm fiber, transmission distances of up to 40 meters were achieved at the same modulation frequency. Again the data were processed offline in MATLAB.

2.1 Optical Camera Communication

OCC (see Fig. 2.1) belongs to the category of OWC. Main types of OWC are: Visible Light Communication (VLC), OCC, and free-space optical (FSO) communications. Among these, OCC is a viable solution for enabling OWC using image sensors as receivers. The transmitter in OCC is a modulated light source. On the receiver side, OCC uses optical cameras, such as those found in smartphones and tablets [5].

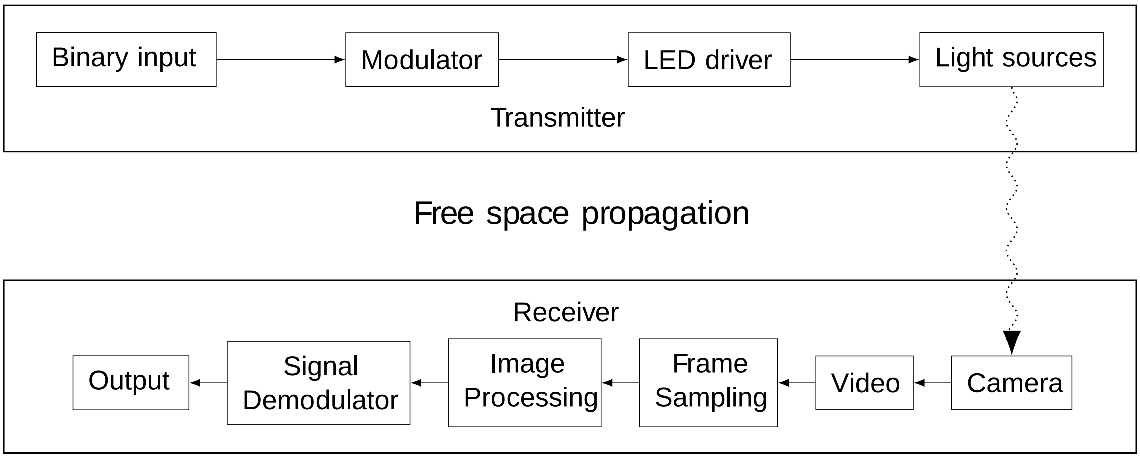

Figure 2.1: Optical Camera Communication diagram (adapted from [6]).

2.1.1 Transceivers

OCC commonly uses modulated visible light signals to transmit data in a manner that remains undetectable to the human eye. LEDs are commonly used as transmitters in OCC systems due to their ability to switch states at a rate su cient for data transmission [7]. OCC systems can transmit signals directly through commercially available LED light sources, signi cantly reducing implementation and installation costs [8].

2.1.2 Receivers

OCC systems employ an image sensor-based commercial camera as a receiver [5]. A simpli ed camera structure consists of an imaging lens, image sensor, and readout circuit. The image sensor comprises a two-dimensional array of photodetectors designed to capture spatial information, which is subsequently processed to generate images for display.

There are two types of image sensor technologies in digital cameras: Charged-Coupled Devices (CCDs) and Complementary Metal-Oxide Semiconductors (CMOSs). Charged-Coupled Device sensors require more power than CMOS sensors because they use an external power source to shift the charge between pixels. Conversely, CMOS sensors use internal transistors to amplify the charge, which reduces power consumption [9]. Complementary Metal-Oxide Semiconductor sensors are also generally cheaper due to their less complex manufacturing process, making them more a ordable for consumer-grade cameras.