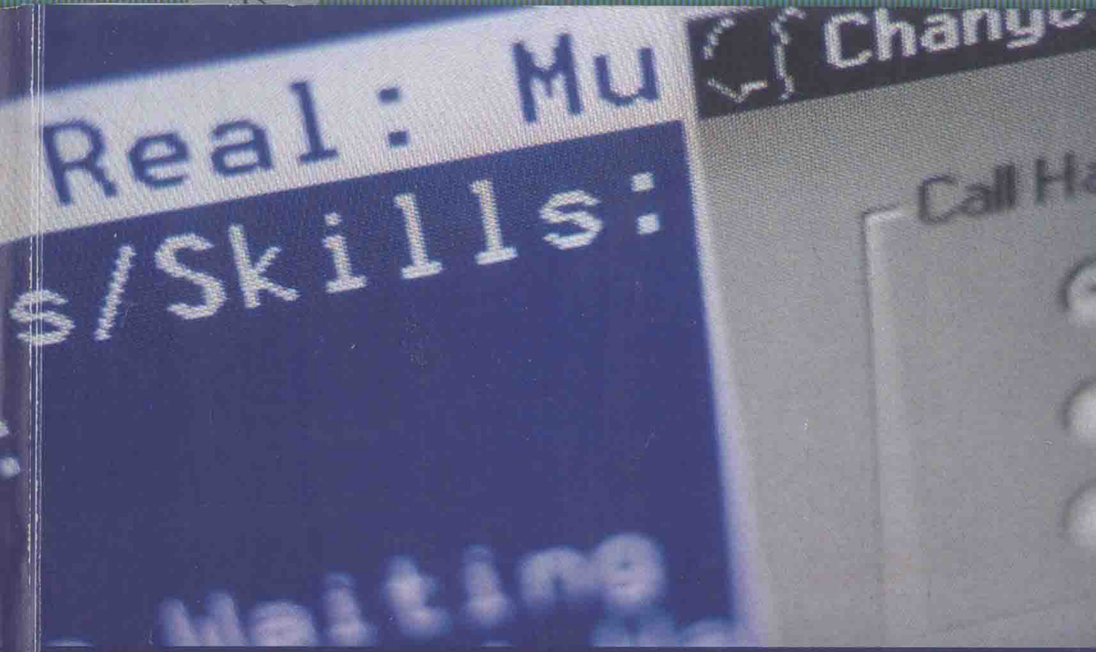

Tobias Kaupp

Human-Robot Collaboration

A Probabilistic Approach

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Nomenclature

Notation

$(\cdot)_k$	$(\cdot)$ at discrete time k
$(\cdot)_{0:k}$	$(\cdot)$ up to time k including k
$(\cdot)_{a:b}$	$(\cdot)$ from time a up to time b
$(\cdot)^n$	number n of $(\cdot)$
$\hat{(\cdot)}$	estimate of $(\cdot)$
$parents(\cdot)$	parents of random variables in $(\cdot)$

General Symbols

k	an index into discrete time
K	total length of time sequence
A	a random variable
x	a scalar state (hidden random variable)
$\mathbf{x}$	a state vector (hidden random variable)
z	a scalar observation (observed random variable)
$\mathbf{z}$	an observation vector (observed random variable)
$\bar{\mathbf{z}}$	fixed observation (value)
$\mathbf{d}$	a vector of actions
d^*	the best action
$\mathbf{i}$	a potential information source
C	cost for obtaining information
$\mathcal{N}$	Normal (Gaussian) distribution
Θ	all parameters
μ,ν	mean vector of a Gaussian
Σ,Ψ	covariance matrix of a Gaussian
Λ	regression matrix of a Gaussian
μ	mean of a 1-dim. Gaussian
σ	standard deviation
ω	regression coefficient of a 1-dim. Gaussian

p	significance level
$F[a, b]$	F-ratio with degrees of freedom a and b

Typefaces

MYCOMPONENT	Software component
`Myinterface`	Component interface
MyNodeName	BN node name
MyDiscreteState	Discrete BN node's state

Abbreviations

AA	Adjustable Autonomy
AI	Artificial Intelligence
ANOVA	Analysis of Variance
BN	Bayesian Network
CPD	Conditional Probability Distribution
CPT	Conditional Probability Table
DAG	Directed Acyclic Graph
DDF	Decentralised Data Fusion
DBN	Dynamic Bayesian Network
EM	Expectation Maximisation
EU	Expected Utility
EUO	Expected Utility of Optimal Action
GMM	Gaussian Mixture Model
GPS	Global Positioning System
GUI	Graphical User Interface
HCI	Human Computer Interaction
HMM	Hidden Markov Model
HRI	Human Robot Interaction
HSM	Human Sensor Model
ID	Influence Diagram
IMU	Inertial Measurement Unit
KF	Kalman filter
kNN	k-Nearest Neighbour
MAP	Maximum A Posteriori
MFA	Mixture of Factor Analysers
ML	Maximum Likelihood
PCA	Principal Component Analysis
SA	Situation Awareness
SAR	Search and Rescue
SLAM	Simultaneous Localisation and Mapping

UAV	Unmanned Aerial Vehicle
UML	Unified Modelling Language
VOI	Value of Information

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Chapter 1

Introduction

1.1 Problem Description and Motivation

This book is concerned with combining the perceptual abilities of mobile robots and human operators to execute tasks cooperatively. It is generally agreed that a synergy of human and robotic skills offers an opportunity to enhance the capabilities of today's robotic systems, while also increasing their robustness and reliability [23][52][155]. Despite the fact that perception of the environment is a critical element in performing any task, *cooperative* human-robot perception has not been studied extensively. Systems which incorporate both human and robotic information sources have the potential to build complex world models, essential for both automated and human decision making.

Although robotic systems are often perceived as a replacement for human labour, there are in fact many opportunities for human-robot cooperation. Mobile robots rarely operate in isolation from humans for several reasons: technical, ethical, and by design. Technical reasons refer to the fact that full robot autonomy is rarely achievable. Today's mobile robots typically operate autonomously for limited periods of time in relatively structured and known environments. The situation is unlikely to change in the near future. In fact, full autonomy may be considered a misnomer because at the very least, operators are required to provide high-level, abstract goals [57]. Ethical reasons for human involvement may arise in situations requiring decisions which only humans are qualified to make. Example application areas include military, search-and-rescue, and health. Finally, people are often an integral part of the system by design: physical interactions between humans and robots occur in assistive robotics and edutainment for example. In addition to the human involvement in robotic systems as described above, an opportunity arises to make use of human resources to improve system performance.

Human-robot cooperation is likely to fulfil this objective because humans and robots cover a wide range of skills in perception, cognition, and manipulation. This book focusses exclusively on the *perceptual* abilities of humans and robots. Human and robotic perception is often complementary in terms of modality, uncertainty, and types of failures. Humans have rich perceptual abilities, especially at higher abstraction levels, *e.g.* human innate pattern recognition skills [59]. Yet, people's performance is known to suffer from great variability between individuals and over time. On the other hand, robotic perception is highly consistent and accurate in measuring lower level descriptions such as geometric properties. At the same time, robotic perception has limited ability to generalise from preprogrammed concepts, *e.g.* in visual object recognition.

Human-robot cooperation typically involves communication. Important research questions for human-robot communication are:

1. What type of information should be communicated?
2. When should communication occur?
3. Who should communicate with whom?
4. What medium should be used for communication?

The space of options available in answering these questions is large and depends on a number of factors. Six factors are identified here: proximity, authority relationship, number of humans and robots, human factors, communication bandwidth, and task priority. The influence of each factor on answering the questions above are discussed next.

Proximity Interactions between humans and robots can either be remote or proximate [68]. If humans and robots are collocated as they are in a service robot application, the communication requirements differ greatly from a remote teleoperation scenario. Likewise, the choice of the communication medium depends on proximity, *i.e.* for close interactions, speech, gestures, haptic interfaces, or social cues may be appropriate while a graphical or textual user interface may be better suited for remote interactions.

Authority Relationship If humans act on a higher level of authority than robots, operators initiate communication and send instructions and commands to robots. If the relationship is more peer-like, communication could involve dialog which either side may initiate [54]. Information exchange related to dialog includes questions, answers, queries, and clarifications.

Number of Humans and Robots If many humans and robots are involved, the question of who communicates with whom becomes important. The objective is to find suitable communication topologies capable of maintaining the scalability of the system [171]. In that context, it is also important to communicate efficiently, *i.e.* only communicate when necessary and maximise the information content per message.

Human Factors The form of communication is greatly influenced by human factors such as expertise [54]. On one end of the spectrum is the robot designer who communicates with robots using a programming language. Ordinary users, on the other hand, may prefer the use of natural language and gestures. Other human factors such as operator workload, stress, and fatigue influence how frequently information should be exchanged.

Communication Bandwidth Limited bandwidth can cause communication problems such as message delays and frequent drop-outs. If bandwidth is a bottleneck, information exchange needs to be efficient as mentioned above. Limited bandwidth may also impose constraints on the possible network topologies [115]. Likewise for the communication medium: broadcasting a video stream to an operator may not be feasible.