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Tracking a Varying Number of People with a Visually-Controlled Robotic Head

Yutong Ban¹, Xavier Alameda-Pineda¹, Fabien Badeig¹, Sileye Ba^{1,2} and Radu Horaud¹

Abstract—Multi-person tracking with a robotic platform is one of the cornerstones of human-robot interaction. Challenges arise from occlusions, appearance changes and a time-varying number of people. Furthermore, the final system is constrained by the hardware platform: low computational capacity and limited field-of-view. In this paper, we propose a novel method to simultaneously track a time-varying number of persons in three-dimension and perform visual servoing. The complementary nature of the tracking and visual servoing enables the system to: (i) track multiple objects while compensating for large ego-movements and (ii) visually-control the robot to keep the person-of-interest in the field-of-view. We implement a variational approximation allowing us to effectively solve the inference problem through the use of closed-form solutions. Importantly, this leads to a computationally light system that runs at 10 FPS. The experiments on the NAO-MPVS dataset confirm the importance of using motor information when tracking multiple persons.

I. INTRODUCTION

Robots are currently on the verge of sharing many common spaces with humans. Exemplar scenarios are the front desk of a hotel, museum guides, elder assistance or entertainment for children. In all these situations, and many others, the robotic platform is required to interact with people and, as part of its low-level behavioral skills, to perform person tracking and visual servoing. In plain words, this means that the robot is supposed to keep track of the position of the people in the scene and, once the person-of-interest has been chosen, keep its visual focus towards that person.

Visual servoing, or how to perform control based on visual information, has been a well-studied problem [1], [2]. Different methods have been developed targeting different applications, such as grasping [3], mobile robot navigation [4] or autonomous aerial vehicles [5]. In this paper we are interested in visual servoing with a robot’s head, which is commonly known as head-eye coordination, and that has been studied in a wide range of applicative scenarios with a *single* object/person of interest [6], [7], [8], [9], [10], [11], [12], [13], [14], [15] using different methodologies such as detect and pursuit, image-feature based tracker, or the extended Kalman filter (EKF).

However, most of the communicative situations of our everyday life are populated with several people and, even if not all of them may constantly be persons of interest, robotic platforms would benefit from joint multiple-person tracking

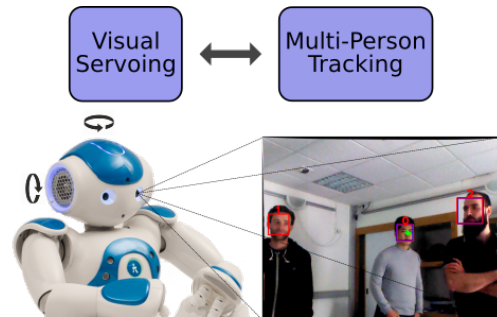


Fig. 1. Schematic overview of the system. The visual servoing module estimates the optimal robot commands and the expected impact of the tracked positions. The multi-person tracking module refines the positions of the persons with the new observations and the information provided by the visual servoing.

and visual servoing capabilities. Compared to single-person scenarios, addressing populated environments is challenging for various reasons. First, computationally cheap face/person detection algorithms often deliver noisy detections or even fail to provide a consistent sequence of bounding boxes. Second, even under the hypothesis of high-quality face detections, we are still left with the task of associating the detections at time t with the previous position estimates. For instance, [16] proposed to use the EKF for each tracked person, often leading to wrong detection-to-person assignments and thus estimatin roaming tracks. More computationally demanding algorithms exist, such as particle-filtering, *e.g.* [17], but their use in on-line applications is rather limited. Third, in out-of-the-lab scenarios, people will continuously appear and disappear from the field-of-view of the robot, and it is highly desirable to have a rough estimate of whether the recently appeared person had previously been seen.

There exist a plethora of methodologies specifically designed to tackle the multiple-object (or person) tracking problem. For example, [18] tackles the problem by combining a sparse representation-based appearance model with a sliding window and [19] proposed the aggregated local flow descriptor and a dynamic graphical model that is optimized off-line. To the best of our knowledge, most of the existing methods are not designed to handle moving cameras, and even if some of them are partially robust to ego-motions, since they need additional background features to estimate camera motions [20]. It is not straightforward to take ego-motion information into account in case it is available. As we experimentally show, this can cause a huge drop on tracking performance, in particular when addressing the aforescribed scenarios.

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In order to overcome this issue, we propose to include into the multi-person tracker the expected impact of the robot’s motion caused by the visual servoing, as schematically shown in Figure 1. To do that, we track all people present in the scene in the three-dimensional space, thanks to the use of a stereo camera rig. Formulating the problem in the three-dimensional world allows us to compute the servoing Jacobian in closed-form, meaning that we can easily estimate the impact of the robot’s motion at any point in the three-dimensional space, and at the tracked positions in particular. This estimate is explicitly taken into account in the tracking formulation. Indeed, we incorporate this information within the tracking probabilistic model, that is solved using a variational Bayes formulation [21]. In our applicative context such a solution is preferred over more classical methods because the overall system is (i) able to handle a number of people varying over time, (ii) robust to appearing/disappearing people and (iii) computationally cheap since all steps are closed-form.

Our contribution is multi-way. First, we propose a joint multi-person tracking and visual servoing system that is able to continuously estimate the three-dimensional position of a time-varying number of people and to encompass the effect of the robot’s motion on this estimation. This complements current studies on visual servoing by providing the ability of tracking multiple objects, and it also complements current studies on MOT by compensating for large ego-movements. Second, we propose a sound probabilistic formulation and a variational approximation allowing to effectively solve the inference problem of the filtering distribution while keeping a reasonably low computational load (the overall system works at 10 FPS). Third, we report a large experimental study on the NAO Multi-Person Visual Servoing (NAO-MPVS) dataset showing, not only that the addressed scenarios are challenging, but also that including the impact of the robot’s motion into the tracking probabilistic framework is of utmost importance for the performance of the system.¹

The remaining of the paper is as follows. Section II presents the probabilistic tracking formulation that is inter-layered with the visual servoing module detailed in Section III. The system’s architecture is described in Section IV, before discussing the experimental protocol and results in Section V and drawing some conclusions in Section VI.

II. MULTIPLE-PERSON TRACKING

We adopt the probabilistic techniques for multiple person tracking recently developed in [21]. Let N_t denote the (time-varying) number of people at time t , and \mathbf{X}_{tn} denote the three-dimensional position of the n -th person at time t . Exploiting three-dimensional position in the joint tracking-servoing paradigm has two prominent advantages. First, the extra depth information leads to a more stable tracker that is also more robust to object occlusions. Second, the three-dimensional formulation allows us to compute the Jacobian

associated to the visual servoing in closed form, and therefore the expected effect of the robot’s motion into the visual image can be computed without any prior knowledge about the person to be tracked (see Section III). This is a crucial feature of the proposed system, since it allows to encompass the effect of the robot control in the tracking framework and therefore *to infer the persons’ position taking the robot’s motion into account*.

Aiming to privilege smooth trajectories, we track the velocity of the person and a bounding box of the face in addition to the position. More formally, the tracking variable is a concatenation of these three variables: $\mathbf{M}_{tn} = [\mathbf{X}_{tn}^T, \mathbf{B}_{tn}^T, \dot{\mathbf{X}}_{tn}^T]^T$. These variables are expressed in the coordinate system of the the robot’s camera. In order to track multiple persons, we set a probabilistic model (Section II-A) and inspired from variational Bayes techniques [22] to derive the filtering distribution (Section II-B). The birth process allowing a time-varying number of people is described in Section II-C.

A. Probabilistic model

The probabilistic model consists of two main components. On one hand, the tracking state dynamics delineates the probabilistic behavior of the hidden state over time. On the other hand, the observation model associates the hidden state at current time-instance \mathbf{M}_{tn} to the observations. Both are described in the following and required in order to compute the filtering distribution.

1) *The state dynamics*: models the prior about the temporal evaluation of a person’s tracking state through the relationship between the two consecutive random variables \mathbf{M}_{tn} and \mathbf{M}_{t-1n} . Indeed, we assume that the sources move independently. Regarding the assignment variable, and since there is no relationship between assignments at different time steps, they are modeled as independent random variables:

$$p(Z_t, \mathbf{M}_t | Z_{t-1}, \mathbf{M}_{t-1}) = \prod_{n=1}^N p(\mathbf{M}_{tn} | \mathbf{M}_{t-1n}) \prod_{k=1}^{K_t} p(Z_{tk}). \quad (1)$$

Since the assignment variables at different time steps are not related, the probability of Z_t does not depend on Z_{t-1} .

The two modeling choices that need to be done at this stage are: the prior probability of the assignment variable Z_{tk} and the dynamic model. A prior, there is no reason to belief that one source is more prone to generate observations than another one and we set $p(Z_{tk}) = \frac{1}{N_t+1}$, for all k . Regarding the dynamics of \mathbf{M}_t , we propose a transition model that takes the robot’s motion explicitly into account. Indeed, let \mathbf{C}_{tn} denote the expected three-dimensional motion of \mathbf{X}_{t-1n} due to the robot’s motion (see Section III). Importantly, \mathbf{C}_{tn} can be computed in closed-form thanks to the three-dimensional formulation. We concatenate \mathbf{C}_{tn} with a 5-dimensional vector of zeros (that would correspond to the expected shift of the bounding box and the velocity), a construct a 8-dimensional vector that for the sake of simplicity we will also denote by \mathbf{C}_{tn} . The explicit computation of \mathbf{C}_{tn} , that will be described

¹<https://team.inria.fr/perception/mot-servoing/>

in details in Section III, allows us to predict when a person would appear/disappear and re-appear in the field-of-view. Notice that, due to the potentially large appearance variation, the use of the geometric proprioceptive information may become crucial for the tracking performance. More formally, we model the transition probability with a Gaussian distribution defined as:

$$p(\mathbf{M}_{tn}|\mathbf{M}_{t-1n}) = \mathcal{N}(\mathbf{M}_{tn}; \mathbf{D}\mathbf{M}_{t-1n} + \mathbf{C}_{tn}, \Lambda_n), \quad (2)$$

where \mathbf{C}_{tn} is the translation associated to the effect of the robot control (since \mathbf{M}_{tn} is expressed in the camera coordinate system, see Section III for details), Λ_n models the uncertainty over the dynamics of the n -th source, and \mathbf{D} is the following matrix:

$$\mathbf{D} = \begin{pmatrix} \mathbf{I}_3 & \mathbf{0} & \mathbf{I}_3 \\ \mathbf{0} & \mathbf{I}_2 & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{I}_3 \end{pmatrix}.$$

This definition of \mathbf{D} is equivalent to have a first order model on the dynamic of the person. In other words, a priori the bounding box and the velocity do not change, while the position changes according to the previous velocity.

2) **The observation model:** provides a principled definition of the probabilistic relationship between the observations and the hidden tracking state. Let us assume that at every time t there are K_t observations, denoted by \mathbf{o}_{tk} , $k \in \{1, \dots, K_t\}$. The way we extract the observations is detailed in Section IV, here we assume $\mathbf{o}_{tk} = [\mathbf{g}_{tk}^\top, \mathbf{a}_{tk}^\top]^\top$, where \mathbf{g}_{tk} (resp. \mathbf{a}_{tk}) provides some geometric (resp. appearance) information of the person.

One of modeling difficulties briefly discussed above is that, given that the detectors are not perfect, misdetections, false positive and noisy detections frequently happen. In order to account for this behavior, we define a categorical random variable $Z_{tk} \in \{1, \dots, N_t\}$ assigning observation k at time t to source Z_{tk} :

$$p(\mathbf{o}_t|Z_t, \mathbf{M}_t) = \prod_{k=1}^{K_t} p(\mathbf{g}_{tk}|Z_{tk}, \mathbf{M}_t) p(\mathbf{a}_{tk}|Z_{tk}), \quad (3)$$

where Z_t and \mathbf{M}_t are defined analogously to \mathbf{o}_t . Notice that, while the geometric information depends on the hidden state \mathbf{M}_t and on the assignment variable Z_{tk} , the appearance only depends on the latter. Implicitly we are assuming that the appearance does not depend on the position in a way that can be intuitively modeled.

For both the geometric and the appearance observations we assume that they can belong either to a clutter class (and write $Z_{tk} = 0$) or to a person. In other words we extended the set in which Z_{tk} takes values with a *fake* garbage class responsible to attract all noisy observations. Observations belonging to this extra class follow a uniform distribution on \mathbf{g}_{tk} and on \mathbf{a}_{tk} . Otherwise, we model the geometric information with a Gaussian distribution:

$$p(\mathbf{g}_{tk}|Z_{tk} = n, \mathbf{M}_t) = \mathcal{N}(\mathbf{g}_{tk}; \mathbf{P}\mathbf{M}_{tn}, \Sigma), \quad (4)$$

where $\mathbf{P} = (\mathbf{I}_5 \mathbf{0}) \in \mathbb{R}^{5 \times 8}$ extracts the three-dimensional position of the source and the size of the bounding box from the state vector \mathbf{M}_{tn} and Σ models the uncertainty of the detector. The model for the appearance follows a Bhattacharya distribution:

$$p(\mathbf{a}_{tk}|Z_{tk} = n) = \mathcal{B}(\mathbf{a}_{tk}; \mathbf{a}_{tn}^*) = \frac{1}{W_\lambda} \exp(-\lambda d_B(\mathbf{a}_{tk}, \mathbf{a}_{tn}^*)), \quad (5)$$

where λ is a positive skewness parameter, $d_B(\cdot)$ is the Bhattacharya distance between feature vectors, W_λ is the normalization constant and \mathbf{a}_{tn}^* is the appearance model closest to the observations \mathbf{a}_{tk} among those that have been previously associated to person n . This is done so as to integrate the high-performance philosophy of tracking-learning-detection [23] into the proposed probabilistic model, and therefore keep on enriching the appearance model with the newly available observations.

B. Variational inference

In order to merge all the previous observations together with the current information gathered at time t , we write the *filtering distribution of the hidden random variables*:

$$p(Z_t, \mathbf{M}_t | \mathbf{o}_{1:t}) \propto p(\mathbf{o}_t | Z_t, \mathbf{M}_t) p(Z_t, \mathbf{M}_t | \mathbf{o}_{1:t-1}), \quad (6)$$

where the second term is the so-called predictive distribution, which is related to the filtering distribution at time $t-1$ by:

$$p(Z_t, \mathbf{M}_t | \mathbf{o}_{1:t-1}) = p(Z_t) \int_{\mathbf{M}_{t-1}} p(\mathbf{M}_t | \mathbf{M}_{t-1}) \sum_{Z_{t-1}} p(Z_{t-1}, \mathbf{M}_{t-1} | \mathbf{o}_{1:t-1}).$$

Since (6) does not accept a computationally tractable closed-form expression, we choose to use a variational approximation [22]. If properly designed, such approximations have the prominent advantage of deriving into closed-form updates for the a posteriori (filtering) probabilities. Concisely, variational approximations consist on imposing a partition over the hidden variables, in our case:

$$p(Z_t, \mathbf{M}_t | \mathbf{o}_{1:t}) \approx \prod_{n=1}^{N_t} q(\mathbf{M}_{tn}) \prod_{k=1}^{K_t} q(Z_{tk}), \quad (7)$$

and then finding the optimal distributions $q(\mathbf{M}_{tn})$ and $q(Z_{tk})$ in the Kullback-Leibler distance sense.

The optimal posterior distribution of the assignment variable $q(Z_{tk})$ writes:

$$q(Z_{tk} = n) = \alpha_{tkn} = \frac{e_{tn} \varepsilon_{tkn} a_{tn}}{\sum_{m=0}^N e_{tm} \varepsilon_{tkm} a_{tm}}, \quad (8)$$

with ε_{tkn} is defined as:

$$\begin{cases} \mathcal{U}(\mathbf{g}_{tk}) \mathcal{U}(\mathbf{a}_{tk}) & n = 0, \\ \mathcal{N}(\mathbf{g}_{tk}, \mathbf{P}\boldsymbol{\mu}_{tn}, \Sigma) e^{-\frac{1}{2} \text{trace}(\mathbf{P}^\top \Sigma^{-1} \mathbf{P} \Gamma_{tn})} \mathcal{B}(\mathbf{a}_{tk}; \mathbf{a}_{1:t,n}) & n \neq 0, \end{cases}$$

where $\text{trace}(\cdot)$ is the trace operator and $\boldsymbol{\mu}_{tn}$ and Γ_{tn} are defined by (9) and (10) below. Intuitively, the assignment of an observation to a person is based on spatial proximity between the geometric observation and the current estimated

position as well as the similarity between the observation's appearance and the person's previous appearances.

The a posteriori distribution for \mathbf{M}_n turns out to be a distribution with mean μ_n and covariance Γ_n given by:

$$\Gamma_n = \left(\Lambda_n^{-1} + \sum_{k=0}^{K_t} \alpha_{tkn} \mathbf{P}^\top \Sigma^{-1} \mathbf{P} \right)^{-1}, \quad (9)$$

$$\mu_n = \Gamma_n \left(\Lambda_n^{-1} (\mathbf{D}\mu_{t-1n} + \mathbf{C}_{tn}) + \sum_{k=0}^{K_t} \alpha_{tkn} \mathbf{P}^\top \Sigma^{-1} \mathbf{g}_{tk} \right) \quad (10)$$

where μ_{t-1n} is the expected position of source n in the previous time step. These two steps are commonly iterated a few times at every time step. Remarkably, this strategy can also be used to learn the parameters of the model, for which we would then be required to derive the so-called M-step. The reader is referred to [21] for an exhaustive discussion.

C. Birth process

Until now we assumed that N_t was known, but this is an unrealistic assumption in real-world applications. We model the variability of N_t with a track birth process, that allows creating new "identities". At time t , after the algorithm has estimated the a posteriori distribution for Z_t and \mathbf{M}_t we perform a test to decide whether a new track is created or not. Intuitively, we test if the observations assigned to the clutter class in the past T_{new} frames are consistent enough to belong to a person that has not been seen before. Let $\mathcal{H} = \{\mathbf{g}_{t'k}, \mathbf{a}_{t'k}\}_{t'=t-T_{new}, Z_{tk}=0}$ such set of observations. If $p(\mathcal{H}) > \tau$, where τ is the probability that these observations are generated by clutter, a new track is created, μ_{tN_t+1} is set to the most recent geometric observation in \mathcal{H} , and the appearance observations are assigned to the new source.

III. VISUALLY-CONTROLLED HEAD MOVEMENTS

In this section we detail the visual servoing model allowing the robot to focus its attention on targets of interest. In order to simplify the discussion we remove the temporal and source indices t and n . The objective of the visual servoing module is to compute the required motor velocity to bring the source of interest to the center of the image. Therefore we need the Jacobian linking the image space to the motor space. Since such relationship is difficult to model, classically one models the motor-to-image Jacobian and then computes the inverse. In our case, we pass by the three-dimensional world and compute the Jacobian as the composite of a camera-world Jacobian and a world-motor Jacobian.

World-to-image Jacobian: We consider the coordinate system associated to the left camera (at the initial head's position) to be the world's coordinate system. This is an arbitrary choice that can be replaced with any other static coordinate system with a simple rigid transformation. The non-linear mapping between world-coordinate and image-coordinate is:

$$\mathbf{V} = \mathbf{K} \frac{1}{X_3} \mathbf{X}, \quad (11)$$

where $\mathbf{X} = (X_1, X_2, X_3)^\top$, $\mathbf{V} = (V_1, V_2)^\top$ and $\mathbf{K} \in \mathbb{R}^{2 \times 3}$ is the matrix of intrinsic parameters of the pinhole camera model. The Jacobian of this transformation writes:

$$\dot{\mathbf{V}} = \underbrace{\mathbf{K} \begin{pmatrix} 1/X_3 & 0 & -X_1/X_3^2 \\ 0 & 1/X_3 & -X_2/X_3^2 \end{pmatrix}}_{\mathbf{J}_{wi}(\mathbf{X})} \dot{\mathbf{X}}, \quad (12)$$

where $\dot{\mathbf{X}}$ is the velocity vector at \mathbf{X} , and \mathbf{V} models the velocity as seen in the left camera image.

Motor-to-world Jacobian: In order to compute the Jacobian relating the velocity at \mathbf{X} and the motor velocity, we first recall that in a general, the velocity of a three-dimensional point when the coordinate system is subject to a rigid motion, namely a rotation $\omega = [\omega_x, \omega_y, \omega_z]^\top$ and a translation $\mathbf{u} = [u_1, u_2, u_3]^\top$, can be expressed as:

$$\dot{\mathbf{X}} = \omega \times \mathbf{X} + \mathbf{u} = \begin{pmatrix} \mathbf{S}(\omega) & \mathbf{u} \end{pmatrix} \begin{pmatrix} \mathbf{X} \\ 1 \end{pmatrix}, \quad (13)$$

where $\mathbf{S}(\omega)$ is the skew symmetric twist matrix representing the exterior product by the three-dimensional vector ω .

In our case, ω and \mathbf{u} depend on the motor yaw and pitch rotation velocities $\dot{\alpha}$ and $\dot{\beta}$ respectively. As shown in the literature [24], for a rotation velocity $\dot{\alpha}$, the velocity at \mathbf{X} can be expressed as:

$$\dot{\mathbf{X}} = \begin{pmatrix} -\mathbf{S}(\mathbf{X}) & \mathbf{I}_3 \end{pmatrix} \begin{pmatrix} \omega_1 \\ \mathbf{u}_1 \end{pmatrix} \dot{\alpha}, \quad (14)$$

where the values of ω_1 and \mathbf{u}_1 are acquired through a calibration phase (see Section IV).

The effect of the pitch is quite similar, with the only difference that, since we first apply the yaw rotation and then the pitch rotation, one has to take into account the effect of $\dot{\beta}$ after the rotation induced by α . Formally we write:

$$\dot{\mathbf{X}} = \begin{pmatrix} -\mathbf{S}(\mathbf{X}) & \mathbf{I}_3 \end{pmatrix} \begin{pmatrix} \mathbf{R}\omega_2 \\ -\mathbf{S}(\mathbf{R}\omega_2)\mathbf{t} + \mathbf{R}\mathbf{u}_2 \end{pmatrix} \dot{\beta}, \quad (15)$$

where ω_2 and \mathbf{u}_2 are obtained through the calibration and \mathbf{R} and \mathbf{t} are the rotation and translation vectors associated to the yaw state α . In all, the motor-to-world Jacobian writes:

$$\dot{\mathbf{X}} = \underbrace{\begin{pmatrix} -\mathbf{S}(\mathbf{X}) & \mathbf{I}_3 \end{pmatrix} \mathbf{L}(\alpha)}_{\mathbf{J}_{mw}(\mathbf{X})} \begin{pmatrix} \dot{\alpha} \\ \dot{\beta} \end{pmatrix}, \quad (16)$$

where $\mathbf{L}(\alpha) \in \mathbb{R}^{6 \times 2}$ is a matrix that implicitly depends on the calibration parameters ω_1 , ω_2 , \mathbf{u}_1 and \mathbf{u}_2 .

Importantly, since this equation is true for any point in the scene \mathbf{X} , it can be applied to estimate predicted people's current position from the previous time step, *i.e.* $\mathbf{D}\mu_{t-1n}$. By doing this, we compute the velocity of the person due to the robot's motion. In other words, at time t , the n -th person will not be around position $\mathbf{D}\mu_{t-1n}$, but close to $\mathbf{D}\mu_{t-1n} + \mathbf{J}_{mw}(\mathbf{D}\mu_{t-1n}) \begin{pmatrix} \dot{\alpha} \\ \dot{\beta} \end{pmatrix}$. This is the value given to the translation due to the robot control:

$$\mathbf{C}_{tn} = \mathbf{J}_{mw}(\mathbf{D}\mu_{t-1n}) \begin{pmatrix} \dot{\alpha} \\ \dot{\beta} \end{pmatrix}. \quad (17)$$

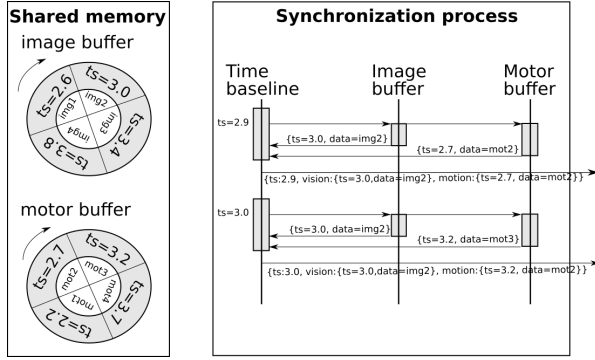


Fig. 2. Robot data synchronization with NAOLab. The shared buffers contain time-stamped data. During the synchronization process, the nearest pairs of data are associated together regarding the time chosen time baseline.

Joint Jacobian: The joint motor-to-image Jacobian is the product of the Jacobians above:

$$\dot{\mathbf{V}} = \mathbf{J}_{im}(\mathbf{X})\mathbf{J}_{mw}(\mathbf{X}) \begin{pmatrix} \dot{\alpha} \\ \dot{\beta} \end{pmatrix} = \mathbf{J}(\mathbf{X}) \begin{pmatrix} \dot{\alpha} \\ \dot{\beta} \end{pmatrix}. \quad (18)$$

To summarize, we are expressly interested in two Jacobian operators. First, the inverse of the motor-to-image Jacobian maps the desired image shift $\Delta\mathbf{V}$ into motor velocities:

$$\begin{pmatrix} \dot{\alpha}_c \\ \dot{\beta}_c \end{pmatrix} = \gamma \mathbf{J}^{-1}(\mathbf{X}_s)\Delta\mathbf{V}, \quad (19)$$

where \mathbf{X}_s is the servo position in three-dimension, $0 < \gamma < 1$ is a scale factor and $\dot{\alpha}_c$ and $\dot{\beta}_c$ are the yaw and pitch velocities to control the robot. Second, we can estimate the impact of these motor velocities onto the people's position by computing \mathbf{C}_{in} using (17) with $\dot{\alpha}_c$ and $\dot{\beta}_c$.

IV. SYSTEM AND ARCHITECTURE

The proposed joint multi-person tracking and visual servoing system is implemented on top of the *NAOLab* middleware (see Section IV), which utilizes the synchronization strategy described in IV to find temporal matches between proprioceptive and perceptive information. Temporal correspondence is insufficient, and the motor-camera calibration procedure depicted in IV is used to estimate the spatial relationship between the motor and the camera coordinate systems. Finally, some implementation details of the joint system can be found in Section IV.

NAOLab: The motivation to use a middleware is multi-fold. First, algorithm implementations can be platform-independent and thus easily portable. Second, the use of computational resources external to the platform is transparent to the developing stage. Third, prototyping is much faster. For all these reasons, we developed a remote and modular layer-based middleware architecture named NAOLab.

NAOLab consists of 4 layers: drivers, shared memory, synchronization engine and application programming interface (API). Each layer is divided into 3 modules devoted to vision, audio and proprioception respectively. The first layer is platform-dependent and interfaces the sensors and actuators

through the network using serialized data structures. The second layer implements a common shared memory that provides a concurrent interface to deserialize data from the robot sensors and implements an event-based control for robot command. The third layer is dedicated to synchronize the audio, video and proprioception data, so that the joint tracking-servoing system handles temporally coherent information. The last layer of NAOLab provides a general programming interface in C++ or Matlab to handle the robot's sensor data and manage its actuators.

Synchronization engine of NAOLab: The synchronization is implemented in the third *NAOLab* layer thanks to a circular data buffer (initialized to a fixed maximum size). The synchronization engine exploits these circular buffers together with the robot clock, and builds packages containing audio, visual and proprioception data whose corresponding time-stamps are close to each other. Figure 2 depicts the synchronization process for the multi-person tracking and visual servoing system (without audio involved), with a time baseline of 0.1 s and a buffer size of four packages.

As illustrated in Figure 3, the robot produces vision and proprioception data at different sampling rates. Each type of data is grabbed by a dedicated parallel process (drivers) who *publishes* the serialized data into the shared memory. After synchronization, the joint tracking and visual servoing module is able to request data from the shared memory or send motor-control commands to the motion drivers.

Motor-camera calibration: As previously discussed, the motor-to-world Jacobian required for the visual servoing depends on four parameters obtained through calibration: ω_1 , ω_2 , \mathbf{u}_1 and \mathbf{u}_2 . In order to do that, we first notice that when the robot's head rotates from α_0 to α_i , there is an extrinsic rotation matrix $\mathbf{Q}_{0 \rightarrow i}$ that can be expressed as a function of ω_1 and \mathbf{u}_1 :

$$\mathbf{Q}_{0 \rightarrow i} = \mathbf{I}_4 + \sin(\alpha_i - \alpha_0) \begin{pmatrix} \mathbf{S}(\omega_1) & \mathbf{u}_1 \\ \mathbf{0} & 0 \end{pmatrix} + (1 - \cos(\alpha_i - \alpha_0)) \begin{pmatrix} \mathbf{S}(\omega_1) & \mathbf{u}_1 \\ \mathbf{0} & 0 \end{pmatrix}^2. \quad (20)$$

At the same time, thanks to the cameras, the external matrix can be estimated with visual information. Indeed, the images of a static chessboard are recorded before and after the rotation, and by manually detecting the chessboard in the image, one can estimate the extrinsic matrix $\tilde{\mathbf{Q}}_{0 \rightarrow i}$. Based on the previous equation and on the properties of the trigonometric functions one can write:

$$J(\omega_1, \mathbf{u}_1) = \sum_i \left\| 2 \sin(\alpha_i - \alpha_0) \begin{pmatrix} \mathbf{S}(\omega_1) & \mathbf{u}_1 \\ \mathbf{0} & 0 \end{pmatrix} - \tilde{\mathbf{Q}}_{0 \rightarrow i} + \tilde{\mathbf{Q}}_{i \rightarrow 0} \right\|_F^2$$

where $\|\cdot\|_F$ is the Frobenius norm. This cost function is then minimized to find the optimum values for the calibration parameters ω_1 and \mathbf{u}_1 . The analogous procedure is repeated for the calibration parameters ω_2 and \mathbf{u}_2 .

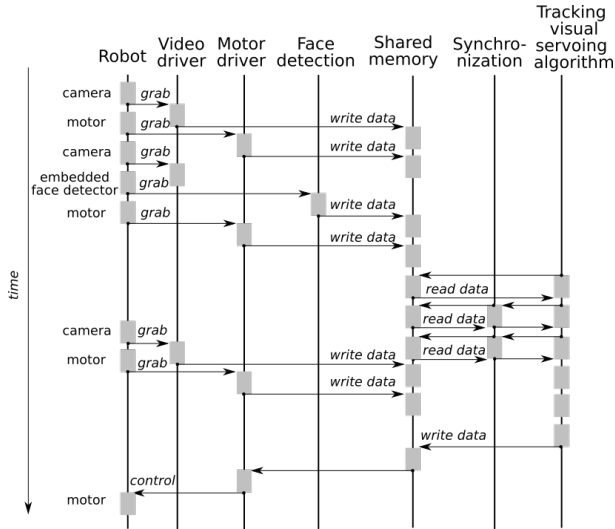


Fig. 3. Data temporal flow chart: the drivers published serialized data into the shared memory. After synchronization, the joint tracking and servoing algorithm requests the data from which computes the appropriate motor control command, sent to the motor drivers through the shared memory.

Implementation details: The overall system is implemented in C++, within the middleware framework described in Section IV. For the sake of reproducibility, we use the face detector and descriptor built-in on NAO, *i.e.* provided by NAO’s API. The geometric observations, \mathbf{g}_{jk} are face bounding boxes (image position, width and height). The position of the bounding box from the left and right camera images is combined by means of epipolar geometry, and triangulation to recover 3D face position. The face appearance descriptor is based on color histograms. Importantly, the detector and descriptor can be replaced or combined with other techniques thanks to the flexibility of the proposed probabilistic model for tracking. The detection and description of faces runs at 10 frames per second (FPS). Since the joint tracking-servoing computational load is less than 70 ms per time step, we are able to provide an on-line implementation of the joint multi-person tracking and visual servoing system.

The proposed variational model is governed by several parameters. Aiming at providing an algorithm that is dataset-independent and that features a good trade-off between flexibility and performance, we set the observation covariance matrix Σ and the state covariance matrix Λ_n automatically from the detections. More precisely, both matrices are imposed to be diagonal; for Σ , the variances of the three-dimensional position, of the width, and of the horizontal (resp. vertical) speed are $1/2$, $1/2$ and $1/4$ of the average detected width (resp. height). The rationale behind this choice is that we consider that the true detection lies approximately within the width and height of the detected bounding box. Regarding Λ_n , the diagonal entries are half of the tracked width and 5 times of motor speed. The window length chosen for the birth process is $T_{new} = 4$.

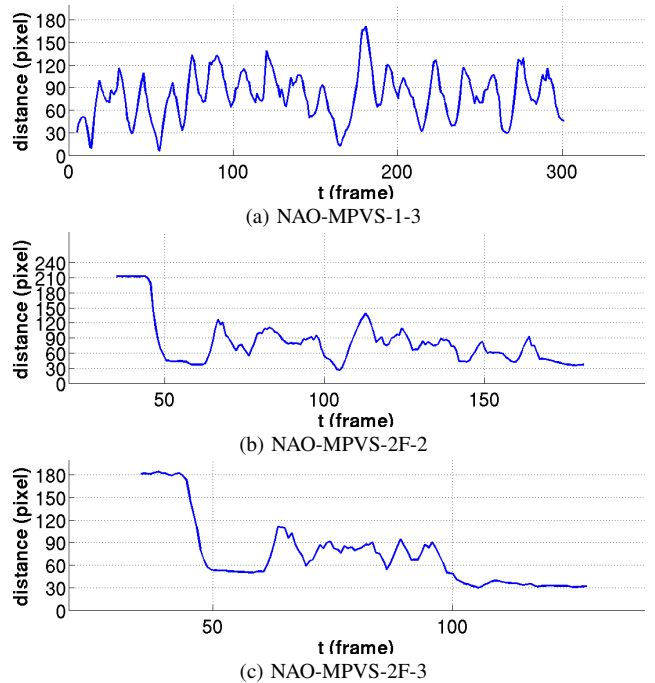


Fig. 4. The distance between tracked person and left camera image center (in pixels) over time (in frames) for three different sequences.

V. EXPERIMENTS

The proposed joint multi-person tracking and visual servoing system is evaluated on a series of scenarios using the NAO robot. Both left and right cameras provide VGA images, which is 640×480 pixels. Ten different sequences have been recorded in a regular living room scenario with its usual lighting source and background, where various people were moving around. The recorded sequences are thus challenging because of illumination variations, occlusions, appearance changes, and people leaving the robot field-of-view. We tried two different high-level control rules: (i) the robot should servo the first tracked person and (ii) the robot should sequentially change the pursuit person every three seconds. The sequences with the servoing-tracking results are publicly available². The sequences are named with the following scheme: NAO-MPVS-NS-P, which stands for NAO Multi-Person Visual Servoing, N is the number of people present in the sequence (although not constantly visible), S defines the strategy when $N > 1$ (“F” for following the first tracked person and “J” for jumping every three seconds) and P for the trial. For instance NAO-MPVS-1-1, is the first trial of a scenario involving one person, while NAO-MPVS-2J-3 is the third trial of a scenario involving two people and the control rule set to “jumping”. In the following, we provide both quantitative and qualitative evaluation of both the visual servoing and of the multi-person tracking.

Visual servoing: Figure 4 shows the distance in pixels from the tracked person to the left camera image center over time, for three different sequences of the dataset, all under the servoing strategy of following the first tracked person.

²<https://team.inria.fr/perception/mot-servoing/>

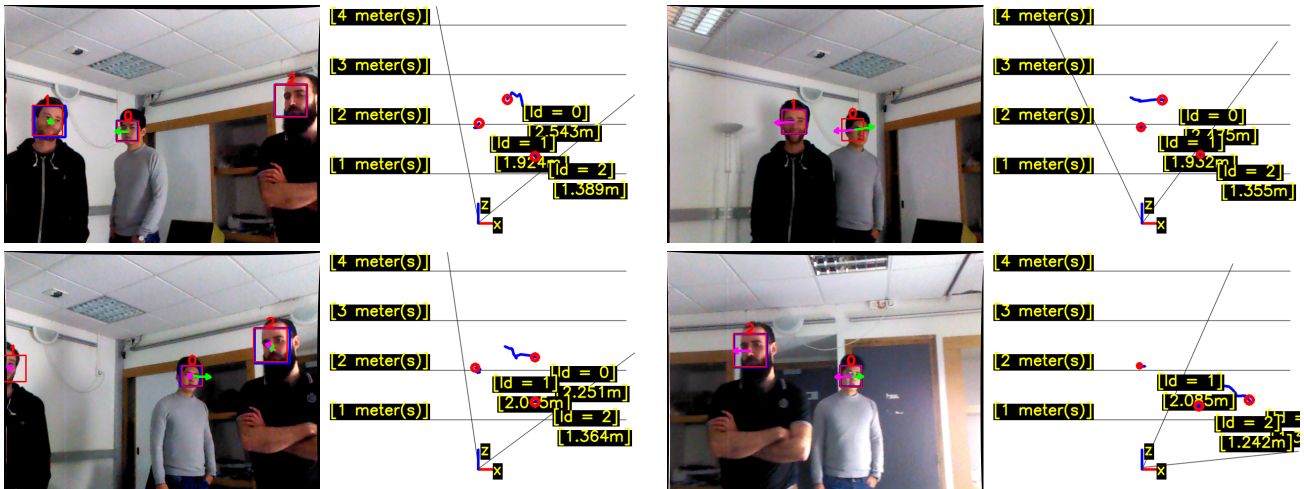


Fig. 5. Left: robot left camera view, red bounding boxes represent the three-dimensional tracking results projected on the image, blue bounding boxes represents three-dimensional face-detection, green arrows represent people’s self-velocity, magenta arrows represent the velocity due to the robot control. Right: scenario bird-view, red circles represent current tracking positions and the blue lines represent tracked people’s trajectories. Example results are from NAO-MPVS dataset sequence NAO-MPVS-3F-1

We can clearly see the oscillation due to the lag between the person’s motion and the control response. Remarkably, shortly after each of the person’s movements, the servoing mechanism position back the person in the image center. Indeed, after a few seconds the distance between the tracked person and the image center has decreased to below 30 pixels. Furthermore, if we compute the average distance for all frames of all sequences (*i.e.* almost 2,000 frames), we obtain an average distance of 80.1 pixels, indicating the that proposed system is able to approximately maintain the person’s face at the image center.

Qualitatively speaking, Figure 5 shows four frames of the most challenging sequence in the dataset, NAO-MPVS-3F-1. This sequence involves three people, among which the tracked one passes behind the other two. Each of the frames shows the marked-up left camera image together to a bird-view representation of the tracked scene. While in the marked-up image we can see the face detection (blue), the tracked bounding box with the tracking ID (red), the target motion due to the robot control (magenta) and the target’s self-motion (green), in the bird-view we can see the tracking ID and the trajectories. We can observe different prominent characteristics of the proposed system. Firstly, the ability to separate the image motion due to the robot control, from the image motion due to the natural movements of the target allows for the estimation of a smooth trajectory in the three-dimensional space. Secondly, the algorithm is able to keep a rough estimate of the positions of the targets that are out of the field of view, and even more important, to correctly re-assign the identify to a re-appearing person thanks to the cooperation of the state dynamics and appearance model. Thirdly, the capacity of the system to add a create a new track when a new person appears in the field-of-view thanks to the birth process. Finally, robustness to identify switches, even with illumination and appearance changes, occlusions and the robot’s self-motion.

TABLE I
COMPARISON OF TRACKING RESULT W/O AND W CONTROL BY MOT METRICS ON THREE SEQUENCES WITH INCREASING COMPLEXITY.
↑ : THE HIGHER THE BETTER
↓ : THE LOWER THE BETTER

| Sequence | Ctrl | MOTA(↑) | MOTP(↑) | FP(↓) | FN(↓) | IDs(↓) |
|---------------|------|-------------|-------------|------------|------------|----------|
| NAO-MPVS-1-1 | w/o | 92.1 | 67.2 | 9 | 9 | 0 |
| | w/ | 91.3 | 68.7 | 10 | 10 | 0 |
| NAO-MPVS-2J-1 | w/o | 52.8 | 67.1 | 93 | 207 | 2 |
| | w/ | 81.6 | 68.0 | 30 | 88 | 0 |
| NAO-MPVS-3J-1 | w/o | 35.8 | 62.3 | 159 | 433 | 19 |
| | w/ | 63.1 | 62.1 | 83 | 268 | 0 |
| Overall | w/o | 48.8 | 65.0 | 261 | 649 | 21 |
| | w/ | 73.1 | 65.3 | 123 | 366 | 0 |

Multi-person tracking: We have also evaluated the impact of the visual servoing from the multi-person tracking perspective. Aiming to this, we compared the performance of the system when using/discarding the image-motion due to the robot control. In more detail, we manually annotated the position of the persons in three different sequences of increasing complexity (NAO-MPVS-1-1, -2J-1 and -3J-1) and we computed the following standard multi-person tracking evaluation metrics [25]: *multiple-object tracking accuracy* (MOTA), *multiple-object tracking precision* (MOTP), *false positives* (FP), *false negatives* or *missed targets* (FN) and *identity switches* (ID). While for MOTA and MOTP are the higher the better, for the rest are the lower the better. Table I reports all these measures with (w/) and without (w/o) using the impact of the robot control (Ctrl) on the targets’ position, *i.e.* C_m .

In light of the results, we can see that indeed NAO-MPVS-1-1 is an easy sequence. Indeed, the only person to be tracked does not perform large movements. It is therefore not surprising that (i) the performance measures are very high and (ii) there is no much performance difference when adding the impact of the control variable. When the complexity of the scenario increases (more people to track, larger movements) the proposed tracking framework including motor

information leads to higher accuracy and less FP/FN/IDs results. This difference is specially remarkable in the case of the NAO-MPVS-3J-1 sequence, showing that tracking based only on the appearance and the position of people is not sufficient when multiple people need to be tracked, while at the same time the robot performs some movements. We also notice that the MOTP measure is not strongly affected by the information provided by the robot control, and this is expected. Indeed, MOTP measures the tracking precision in terms of how much do the bounding boxes of the detected positives overlap with their assigned true positives. In other words, if a detected positive is too far from all true positives, it counts as a FP, but is not computed as a precision error. This confirms our hypothesis that the use of C_m is crucial to correct large deviations of the tracking estimates due to the motor control; And at the same time result shows that it is not specially helpful to refine these tracking estimates. In other words, the use of C_m is complementary to developing precise tracking methodologies which are able to provide very accurate bounding box localization once the large corrections due to the motor-control are applied.

Overall the proposed joint multiple-person tracking and visual servoing framework leads to promising results even in sequences which contain large and frequent robot motions under challenging illumination conditions. Remarkably, the method is able to systematically keep the right person identity for all three sequences. This feature is highly desirable for numerous applications and critically depends upon the use of motor information during tracking.

VI. CONCLUSIONS

This paper proposes a novel joint variational multi-person tracking and visual servoing system which is able to continuously estimate the three-dimensional position of a time-varying number of people and to encompass the effect of the robot's ego-motion. In addition, we propose a probabilistic formulation and a variational approximation allowing to effectively solve the inference problem while keeping a reasonably low computational cost (the overall systems works at 10 FPS). Furthermore, thanks to the motor information, the system can separate people's self-motion from the robot's ego-motion, leading to more robust tracking capabilities. The experimental study on the NAO Multi-Person Visual Servoing dataset confirms our hypothesis that including the robot's ego-motion into the tracking probabilistic framework is of utmost importance for the performance of the system. In the future, we will investigate (i) the calibration of other motors (e.g. robot's leg-joint), thus compensating for the full ego-motion and (ii) the combination of audio information to construct a tracking system based on audio-visual information, thus able to track outside the camera field-of-view.

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