Biomechanic motion capture system

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Abstract. This paper proposes an optical motion capture system based on markers that facilitates biomechanical analysis from people movements. The system consists of separate blocks, giving an overall solution which allows to easily modify or replace components. Guidelines are described for generating a virtual laboratory from which to obtain a database with sequences of synthetic videos and explore the characteristics required for a laboratory based on optical capture of markers to facilitate processing. A set of metrics is presented to measure the performance of each block and the overall system. Tests on the software implemented reflected that it has an accuracy in the order of centimeters on sequences obtained in controlled environments. These results are acceptable considering that the algorithms used in each block are of low complexity and can be optimized.

1. Introduction

The video analysis is an essential tool for study and data collection. Tracking reference points can be used to calculate position and other associated variables such as speed, acceleration and therefore movement. The manual tracking of those points can be tedious so it is necessary to have a tool to perform this task automatically. Some examples that illustrate these needs are: at *health care level* in the area of *physiotherapy*, *biomechanics academic research*, *measures of performance* in professional sports and *3D animation*. These examples define use cases with different characteristics, so the search for a single solution that covers particular needs of all of them is a complex issue. To have these tools is essential for professional teams needs, where other alternatives are high-cost commercial products.

This project sought to perform a basic and functional open source video analysis application to provide solution to the above mentioned needs, either using an existing open source project as starting point, or developing a prototype software that covers the entire problem generally, and then extend the application for other use cases.

The system created aims, under certain controlled conditions, to obtain the spatial coordinates from a number of points on a subject. To do this the subject, with a black suit and white markers, is placed in an environment with adequate lighting, then filmed with multiple cameras over time. This information is transfered to the computer and processed to obtain the 3D trayectories of all markers.

Working from the algorithm proposed by Herda [2], it is proposed a reproducible version from it, containing measures of performance on each stage, as well as a methodology for designing a virtual laboratory, developing a complete test system.

2. State of the art

We have focused our work on developing a system with acceptable accuracy but also affordable, so we direct the search towards systems which uses markers and normal cameras. While it was not found much literature reviewing the state of the art of such systems, we did find articles about full or partial implementations of this kind of systems. Within this bibliography there is a thesis produced by Herda *et al.* [2]. This was used as a base for the development of our system because the thesis is quoted on many articles and the system described has the features which we were looking for. However, the explanation of some processes in this thesis has some ambiguities.

We have also searched for currently available systems. The commercial motion capture systems use mostly infrared cameras and are known for their good performance but many of them are very expensive. We haven't found free software alternatives that perform all stages of a motion capture system but there are some tools available that allow to perform some of these stages separately.

In order to develop and test our system we searched for video sequences of motion capture. Many databases were found but they were all ruled out for not conforming to the assumptions made in this paper. These databases were designed for making motion captures with infrared cameras so the laboratory conditions are not adequate for normal cameras. However these databases were used to generate a virtual laboratory which is described in section 3.

3. Sequence generation

In order to implement, test and compare the different types of algorithms developed for the system, it is desirable to have multiple 2D video motion sequences obtained from cameras located in a previously conditioned closed 3D environment. As well as the corresponding ground truth from 2D and 3D motion data, along information available about the calibration of cameras used to the capture the markers on the patient.

Laboratory Features. It is necessary to pay attention to the relationship between some variables when designing a suitable laboratory for optical capture system based on markers. The capture space and patient clothing should contrast with markers, lighting should be uniform and be out of sight to the cameras. About the last hypothesis, care must be taken with resolution of the cameras, minimum shutter times and their distribution in capture space.

Virtual Laboratory. Using 3D animation suite of free and open source Blender, a virtual laboratory for motion capture is generated, where synthetic motion sequences are obtained along their respective videos of a 3D virtual model.

The skeleton model contains motion information, the same obtained from database MotionBuilder-friendly version offered by cgspeed which contains the BVH sources that come from real motion captures of Carnegie Mellon University Motion Capture Database (CMU). While video sequences obtained are all necessary for further analysis, to generate these sequences through a controlled virtual environment allows testing on multiple configurations and obtaining the exact capture information of the environment.

Blender allows to extend the functionality through Python scripts, automating various stages in the development of new sequences and exporting the information to other programming languages. For more details on the implementation of virtual laboratory as well as sequence generation, refer to [1].

4. Algorithm description

A motion capture system with the necessary characteristics to achieve the objective of this project must implement four general blocks: *calibration*, *segmentation*, *reconstruction* and *tracking*. Figure 1 shows a scheme of the system to be implemented, every green block indicates a stage output, being at the same time next block input.

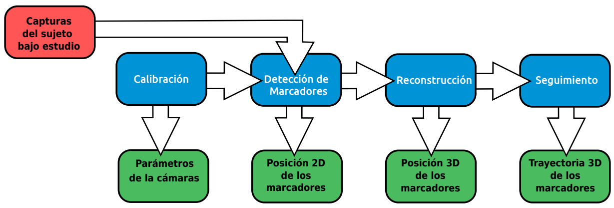

Figure 1. Block diagram of complete system.

It is important to highlight the independence between blocks, allowing to modify or easily optimize the system in future stages.

5. Implementation

The following chapters describes the operation of each stage of the process of motion capture, as well as their implementation.

5.1. Camera calibration

A valid calibration method was required for the arrangement of cameras used in the virtual environment described in section 3. Different existing implementations were tested such as two toolboxes developed in *Matlab*. The calibration method was simulated in *Blender* with *Python scripts* and the resulting images were processed with these toolboxes. Further description of the methodology and simulations can be found in [1].

One of these toolboxes is the *Automatic Multi-Camera Calibration Toolbox (amcctoolbox)* [10], which uses a checkerboard as a calibration object. This method, although has good accuracy results [6], it is not flexible enough for our virtual environment with many cameras because in some cases manual intervention is required. The other toolbox is the *Multi-Camera Self-Calibration Toolbox* [9]. This method captures the movement of a point light source, for example a led light bulb. For each frame there is a 3D point in space in a different position and its corresponding projection in each camera. The average re-projection error is less than 0.13 pixels for all cameras. This method seems simple and suitable for a system of many cameras.

5.2. Markers Detection

Markers detection block, can be divided in two parts: *segmentation* and *objects filter*. Algorithm makes the detection through the following process:

(i) Get each frame from video input.
(ii) Take a frame and segment it using Otsu's umbralization.
(iii) Detect markers from segmented image.
(iv) Write detected markers position in an XML file.
(v) Take the following frame and repeat process from step two.

5.2.1. Detection stages description *Segmentation* block uses umbralization generating thresholds with three class Otsu's method[7].
Filtering stage is just a classification of segmented objects. Since objects to be detected have relatively simple shapes (white circles on dark background) and laboratory conditions are controlled during the capture, this stage not required to implement a complex algorithm. Particularly, it was implemented a circular object detector based on geometric moments[3] and an area based filter.

5.2.2. Results It was observed that results on segmentation stage strongly depends from capture conditions and calculated threshold. Special care must be taken in capture conditions since if not meet the established, results are not entirely satisfactory. On the other hand, if captures are made in the established conditions, obtained results are acceptable (Figure 2).

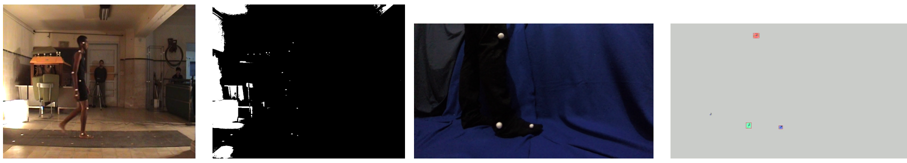

Figure 2. *Left*: original image from a sequencue without capture hypothesis. *Left center*: segmentation results without capture hypothesis. *Right center*: Original capture from a real sequence under capture hypothesis. *Right*: Detected markers.

5.3. Reconstruction

Segmentation output has, for each camera and for each frame of a sequence, a set of coordinates (x, y) that locate the position in the image of detected markers. The reconstruction process is to obtain the position of the markers in space, from 2D markers position in at least two retinas.

The reconstruction process presented was inspired by Herda's work and consists of three basic steps:

(i) Find the correspondence between points in different retinas.

(ii) Select best match.

(iii) Reconstruct and check rest of the retinas.

5.3.1. Algorithm The implemented algorithm receives as input 2D points of detected markers and returns as output reconstructed 3D points. Figure 3 is a diagram of the algorithm presented.

Associating 2D points. This block receives as input the coordinates of detected points and projection matrices of the cameras, returning to each point a list sorted by relevance of the existing partnerships with points on other cameras.

Best match. From the list of associations between pairs of cameras it is necessary to choose one that possesses more probability to form the pair corresponding to the projection of a 3D marker views on such images. From each pair of cameras is taken the association which maintains the shorter distance and contains valid points, discarding the rest. To choice the pairs of cameras were considered two cases. The first one evaluates each camera with all remaining and the second one considers the arrangement of cameras in space and match the adjacent cameras consecutively.

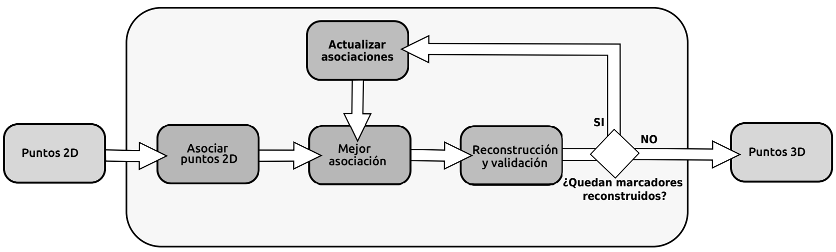

Figure 3. Block diagram of reconstruction algorithm.

Algoritmo: *Asociar puntos 2D.*
$\forall$ cámara i y $j \neq i$
  $\forall$ punto x_{in} en cámara i
    Hallar recta epipolar l_{in} en cámara j
    $\forall$ punto x_{jm} en cámara j
      b_{nm} = distancia(x_{jm}, l_{in})
    $D_{ij} = \{b_{nm}\}$, posibles asociaciones

Algoritmo: *Mejor asociación.*
$\forall$ cámara i y $j \neq i$
  $\tilde{D}_{ij}$ = válidos(D_{ij})
  b^{ij}_{nm} = mínimo$(\tilde{D}_{ij})$
  $x_{in}x_{jm}$ pareja asociada a b^{ij}_{nm}
  d_{ij} = distancia entre rayos de x_{in} e x_{jn}
d = mínimo$(\{d_{ij}\})$

3D reconstruction and Validation. Couple of points $x_i x_j$ of cameras i and j respectively, reconstruct a valid point 3D X_{ij} if there is at least one x_k in camera $k \neq i, j$ such that $X_{ik} \in$ sphere(X_{ij}, δ), to certain threshold δ.

Update matches The couple who reconstructs X_{ij} as well as x_k points who validate this reconstruction are removed. Iteration continue repeating the process with next pairs of best associated cameras. Finally iterative process stops when the number of reconstructed markers equals number of markers that the person has, equal to maximum number of reconstructions indicated, or not valid 2D points such that a partnership between different points of view can be established.

5.4. Seguimiento

El seguimiento de trayectorias se realiza sobre una ventana deslizante de tres a cuatro cuadros enlazando los puntos reconstruidos de manera de mantener un movimiento lo mas suave posible. Esta metodologa fue utilizada por Herda [2] en su trabajo basndose en los estudios de Malik, Drako, Papantoniou [5] . *Algoritmo.* Sea la trayectoria de un marcador enlazada hasta el instante [f] sobre la cual desea buscarse su prximo punto en [f+1], el movimiento entre [f-1] y [f] es prolongado para establecer un centro de bsqueda y encontrar el punto reconstruido que mejor contina la trayectoria como se muestra en la Figura 4 .

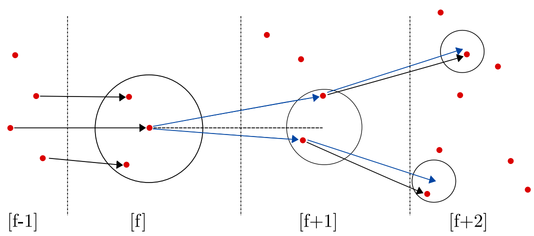

Figure 4. Seguimiento en cuatro cuadros, siendo [f] el cuadro actual que queremos seguir en [f+1]. (Fuente Human movement science 20(3), 313341 [2]) .

Se presentan tres posibles casos al buscar puntos reconstruidos:

- Si solo se encuentra un punto reconstruido se agrega a la trayectoria para el cuadro [f+1], buscando el mas cercano a la estimacin calculada como aquella que mejor se aproxima a una trayectoria de tres puntos con aceleracin mnima
- En el caso de encontrar mas de un punto cada posible candidato es evaluado para realizar una segunda estimacin hacia [f+2] de forma que la aceleracin entre [f-1], [f] y el candidato en [f+1] sea la misma que entre [f], el candidato en [f+1] y la estimacin en [f+2]. Luego de todos los posible caminos en cuatro cuadros, se elige el de menor variacin de aceleracin.
- Si no se encuentra ningn punto, se procede a aumentar de forma limitada el radio de bsqueda en [f+1] de forma excepcional. Esto se hace para continuar trayectorias que entran en estado de reposo y el ltimo movimiento conocido es nulo o muy pequeo.

Si una trayectoria queda trunca durante el enlazado, se intenta recuperar prolongando el movimiento en prximas cuadros para encontrar puntos reconstruidos cercanos a las estimaciones y extrapolar los puntos intermedios. Por otro lado, se implementan umbrales para definir lmites sobre la aceleracin de los enlaces obtenidos y detectar discontinuidades durante el seguimiento.

Estas medidas permiten detectar trayectorias individuales sobre los puntos reconstruidos, detectar de forma simple posibles discontinuidades, y estimar reemplazos en casos de prdidas. La captura en la Figura 5 corresponde a la marcha y se resaltan las trayectorias individuales de puntos de la pierna as como un esqueleto simple generado para visualizar la evolucin entre marcadores.

El conjunto de puntos reconstruidos puede ser sometido a otros algoritmos de seguimiento

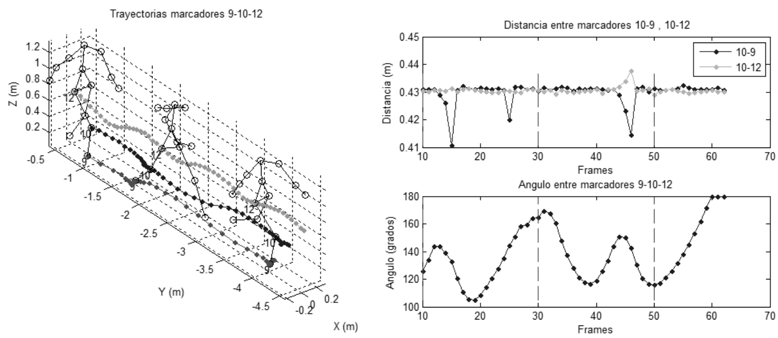

Figure 5. Posibles restricciones en ngulo y distancia, para el caso de la pierna en marcha. Izquierda: trayectorias de marcadores de pierna. Derecha: distancia y ngulo entre marcadores de la pierna.

como Kalman [4] requiriendo la inicializacin de modelos, o algoritmos basados en restricciones ms fuertes que utilicen las distancias relativamente constantes entre marcadores de los miembros y ngulos continuos entre articulaciones, requiriendo un mayor estudio de las caractersticas del sujeto y movimiento a capturar.

6. Results

Metrics established in HumanEva [8] were used to compare sets of data to each individual block output with that retrieved reference set in the ground truth database, seeking first correspondence between points and then Euclidian distance (in 2D for cameras and 3D for reconstructed space) between points of both sets.

Error detection of markers in each one of the cameras does not exceed a couple of pixels in case of cameras with resolution in image 1600×600. It is possible to reduce resolution of the cameras up to 800×300 and maintain the same results, but in lower resolutions it begins to degrade the rate of markers detection in single camera, which impairs the following stages. Another tests were performed injecting noise in detection block and measuring impact in later stages, results show that system can work with up to three pixels of error without significantly compromising the final error.

If cameras are on the previous error condition, full coverage with 17 cameras surrounding capture space allows us to reconstruct all paths with an error below one centimeter with close to three centimeters maximum errors. Results are maintained within these limits using eight cameras, one pair in each corner of the capture space. The project documentation [1] shows how under certain conditions can further reduce number of cameras while maintaining acceptable performance.

7. Conclusions

An optical motion capture system based on markers was obtained completely, from videos captured from a person in a lab environment with controlled conditions, it manages to obtain 3D position of markers in the body of the person, obtaining movement with accuracy in order of centimeters.

Furthermore, this implementation separates each process step in different modules capable of operating independently, allowing to work with any acquisition system that generates pictures to analyse.

When testing with real sequences from three cameras in a laboratory outside the motion capture hypothesis, problems occur in the stages of segmentation and reconstruction. Performing background subtraction on sequences and modifications on reconstruction block can achieve better results although barely acceptable. This verifies how strong the effect a poor methodology of captured data can have in further steps in the motion capture system.

This work does contribute on reproducibility and design methodology in the area through a structured full motion capture system.

8. Preparing your paper

`jpconf` requires LaTeX 2_ε and can be used with other package files such as those loading the AMS extension fonts `msam` and `msbm` (these fonts provide the blackboard bold alphabet and various extra maths symbols as well as symbols useful in figure captions); an extra style file `iopams.sty` is provided to load these packages and provide extra definitions for bold Greek letters.

8.1. Headers, footers and page numbers

Authors should *not* add headers, footers or page numbers to the pages of their article—they will be added by IOP Publishing as part of the production process.

8.2. `jpconf.cls` *package options*

The `jpconf.cls` class file has two options ‘a4paper’ and ‘letterpaper’:

```
\documentclass[a4paper]{jpconf}
```

or

```
\documentclass[letterpaper]{jpconf}
```

Table 1. `jpconf.cls` class file options.

Option	Description
`a4paper`	Set the paper size and margins for A4 paper.
`letterpaper`	Set the paper size and margins for US letter paper.

The default paper size is A4 (i.e., the default option is `a4paper`) but this can be changed to Letter by using `\documentclass[letterpaper]{jpconf}`. It is essential that you do not put macros into the text which alter the page dimensions.

9. The title, authors, addresses and abstract

The code for setting the title page information is slightly different from the normal default in LaTeX but please follow these instructions as carefully as possible so all articles within a conference have the same style to the title page. The title is set in bold unjustified type using the command `\title{#1}`, where `#1` is the title of the article. The first letter of the title should be capitalized with the rest in lower case. The next information required is the list of all authors' names followed by the affiliations. For the authors' names type `\author{#1}`, where `#1` is the list of all authors' names. The style for the names is initials then surname, with a comma after all but the last two names, which are separated by 'and'. Initials should *not* have full stops. First names may be used if desired. The command `\maketitle` is not required.

The addresses of the authors' affiliations follow the list of authors. Each address should be set by using `\address{#1}` with the address as the single parameter in braces. If there is more than one address then a superscripted number, followed by a space, should come at the start of each address. In this case each author should also have a superscripted number or numbers following their name to indicate which address is the appropriate one for them.

Please also provide e-mail addresses for any or all of the authors using an `\ead{#1}` command after the last address. `\ead{#1}` provides the text Email: so `#1` is just the e-mail address or a list of emails.

The abstract follows the addresses and should give readers concise information about the content of the article and should not normally exceed 200 words. **All articles must include an abstract**. To indicate the start of the abstract type `\begin{abstract}` followed by the text of the abstract. The abstract should normally be restricted to a single paragraph and is terminated by the command `\end{abstract}`

9.1. Sample coding for the start of an article

The code for the start of a title page of a typical paper might read:

```
\title{The anomalous magnetic moment of the
neutrino and its relation to the solar neutrino problem}

\author{P J Smith$^1$, T M Collins$^2$,
R J Jones$^{3,}$\footnote[4]{Present address:
Department of Physics, University of Bristol, Tyndalls Park Road,
Bristol BS8 1TS, UK.} and Janet Williams$^3$}

\address{$^1$ Mathematics Faculty, Open University,
Milton Keynes MK7~6AA, UK}
\address{$^2$ Department of Mathematics,
Imperial College, Prince Consort Road, London SW7~2BZ, UK}
\address{$^3$ Department of Computer Science,
University College London, Gower Street, London WC1E~6BT, UK}

\ead{williams@ucl.ac.uk}

\begin{abstract}
The abstract appears here.
\end{abstract}
```

10. The text

The text of the article should should be produced using standard LaTeX formatting. Articles may be divided into sections and subsections, but the length limit provided by the conference organizer should be adhered to.

10.1. Acknowledgments
Authors wishing to acknowledge assistance or encouragement from colleagues, special work by technical staff or financial support from organizations should do so in an unnumbered Acknowledgments section immediately following the last numbered section of the paper. The command `\ack` sets the acknowledgments heading as an unnumbered section.

10.2. Appendices
Technical detail that it is necessary to include, but that interrupts the flow of the article, may be consigned to an appendix. Any appendices should be included at the end of the main text of the paper, after the acknowledgments section (if any) but before the reference list. If there are two or more appendices they will be called Appendix A, Appendix B, etc. Numbered equations will be in the form (A.1), (A.2), etc, figures will appear as figure A1, figure B1, etc and tables as table A1, table B1, etc.

The command `\appendix` is used to signify the start of the appendixes. Thereafter `\section`, `\subsection`, etc, will give headings appropriate for an appendix. To obtain a simple heading of 'Appendix' use the code `\section*{Appendix}`. If it contains numbered equations, figures or tables the command `\appendix` should precede it and `\setcounter{section}{1}` must follow it.

11. References
In the online version of *Journal of Physics: Conference Series* references will be linked to their original source or to the article within a secondary service such as INSPEC or ChemPort wherever possible. To facilitate this linking extra care should be taken when preparing reference lists.

Two different styles of referencing are in common use: the Harvard alphabetical system and the Vancouver numerical system. For *Journal of Physics: Conference Series*, the Vancouver numerical system is preferred but authors should use the Harvard alphabetical system if they wish to do so. In the numerical system references are numbered sequentially throughout the text within square brackets, like this [2], and one number can be used to designate several references.

11.1. Using BibTeX
We highly recommend the `iopart-num` BibTeX package by Mark A Caprio [**?**], which is included with this documentation.

11.2. Reference lists
A complete reference should provide the reader with enough information to locate the article concerned, whether published in print or electronic form, and should, depending on the type of reference, consist of:

- name(s) and initials;
- date published;
- title of journal, book or other publication;
- titles of journal articles may also be included (optional);
- volume number;
- editors, if any;
- town of publication and publisher in parentheses for *books*;

- the page numbers.

Up to ten authors may be given in a particular reference; where there are more than ten only the first should be given followed by '*et al*'. If an author is unsure of a particular journal's abbreviated title it is best to leave the title in full. The terms *loc. cit.* and *ibid.* should not be used. Unpublished conferences and reports should generally not be included in the reference list and articles in the course of publication should be entered only if the journal of publication is known. A thesis submitted for a higher degree may be included in the reference list if it has not been superseded by a published paper and is available through a library; sufficient information should be given for it to be traced readily.

11.3. Formatting reference lists

Numeric reference lists should contain the references within an unnumbered section (such as `\section*{References}`). The reference list itself is started by the code `\begin{thebibliography}{<num>}`, where `<num>` is the largest number in the reference list and is completed by `\end{thebibliography}`. Each reference starts with `\bibitem{<label>}`, where 'label' is the label used for cross-referencing. Each `\bibitem` should only contain a reference to a single article (or a single article and a preprint reference to the same article). When one number actually covers a group of two or more references to different articles, `\nonum` should replace `\bibitem{<label>}` at the start of each reference in the group after the first.

For an alphabetic reference list use `\begin{thereferences}` ... `\end{thereferences}` instead of the 'thebibliography' environment and each reference can be start with just `\item` instead of `\bibitem{label}` as cross referencing is less useful for alphabetic references.

11.4. References to printed journal articles

A normal reference to a journal article contains three changes of font (see table 2) and is constructed as follows:

- the authors should be in the form surname (with only the first letter capitalized) followed by the initials with no periods after the initials. Authors should be separated by a comma except for the last two which should be separated by 'and' with no comma preceding it;
- the article title (if given) should be in lower case letters, except for an initial capital, and should follow the date;
- the journal title is in italic and is abbreviated. If a journal has several parts denoted by different letters the part letter should be inserted after the journal in Roman type, e.g. *Phys. Rev.* A;
- the volume number should be in bold type;
- both the initial and final page numbers should be given where possible. The final page number should be in the shortest possible form and separated from the initial page number by an en rule '– ', e.g. 1203–14, i.e. the numbers '12' are not repeated.

A typical (numerical) reference list might begin

[1] Strite S and Morkoc H 1992 *J. Vac. Sci. Technol.* B **10** 1237
[2] Jain S C, Willander M, Narayan J and van Overstraeten R 2000 *J. Appl. Phys.* **87** 965
[3] Nakamura S, Senoh M, Nagahama S, Iwase N, Yamada T, Matsushita T, Kiyoku H and Sugimoto Y 1996 *Japan. J. Appl. Phys.* **35** L74
[4] Akasaki I, Sota S, Sakai H, Tanaka T, Koike M and Amano H 1996 *Electron. Lett.* **32** 1105
[5] O'Leary S K, Foutz B E, Shur M S, Bhapkar U V and Eastman L F 1998 *J. Appl. Phys.* **83** 826
[6] Jenkins D W and Dow J D 1989 *Phys. Rev.* B **39** 3317

which would be obtained by typing

```
\begin{\thebibliography}{9}
\item Strite S and Morkoc H 1992 {\it J. Vac. Sci. Technol.} B {\bf 10} 1237
\item Jain S C, Willander M, Narayan J and van Overstraeten R 2000
{\it J. Appl. Phys}. {\bf 87} 965
\item Nakamura S, Senoh M, Nagahama S, Iwase N, Yamada T, Matsushita T, Kiyoku H
and  Sugimoto Y 1996 {\it Japan. J. Appl. Phys.} {\bf 35} L74
\item Akasaki I, Sota S, Sakai H, Tanaka T, Koike M and Amano H 1996
{\it Electron. Lett.} {\bf 32} 1105
\item O'Leary S K, Foutz B E, Shur M S, Bhapkar U V and Eastman L F 1998
{\it J. Appl. Phys.} {\bf 83} 826
\item Jenkins D W and Dow J D 1989 {\it Phys. Rev.} B {\bf 39} 3317
\end{\thebibliography}
```

Table 2. Font styles for a reference to a journal article.

Element	Style
Authors	Roman type
Date	Roman type
Article title (optional)	Roman type
Journal title	Italic type
Volume number	Bold type
Page numbers	Roman type

11.5. References to Journal of Physics: Conference Series articles

Each conference proceeding published in *Journal of Physics: Conference Series* will be a separate *volume*; references should follow the style for conventional printed journals. For example:

[1] Douglas G 2004 *J. Phys.: Conf. Series* **1** 23–36

11.6. References to preprints

For preprints there are two distinct cases:

(1) Where the article has been published in a journal and the preprint is supplementary reference information. In this case it should be presented as:

[1] Kunze K 2003 T-duality and Penrose limits of spatially homogeneous and inhomogeneous cosmologies *Phys. Rev.* D **68** 063517 (*Preprint* gr-qc/0303038)

(2) Where the only reference available is the preprint. In this case it should be presented as

[1] Milson R, Coley A, Pravda V and Pravdova A 2004 Alignment and algebraically special tensors *Preprint* gr-qc/0401010

11.7. References to electronic-only journals

In general article numbers are given, and no page ranges, as most electronic-only journals start each article on page 1.

- For *New Journal of Physics* (article number may have from one to three digits)

  [1] Fischer R 2004 Bayesian group analysis of plasma-enhanced chemical vapour deposition data *New. J. Phys.* **6** 25

Table 3. Font styles for references to books, conference proceedings and reports.

Element	Style
Authors	Roman type
Date	Roman type
Book title (optional)	Italic type
Editors	Roman type
Place (city, town etc) of publication	Roman type
Publisher	Roman type
Volume	Roman type
Page numbers	Roman type

- For SISSA journals the volume is divided into monthly issues and these form part of the article number

  [1] Horowitz G T and Maldacena J 2004 The black hole final state *J. High Energy Phys.* JHEP02(2004)008

  [2] Bentivegna E, Bonanno A and Reuter M 2004 Confronting the IR fixed point cosmology with high-redshift observations *J. Cosmol. Astropart. Phys.* JCAP01(2004)001

11.8. References to books, conference proceedings and reports

References to books, proceedings and reports are similar to journal references, but have only two changes of font (see table 3).

Points to note are:

- Book titles are in italic and should be spelt out in full with initial capital letters for all except minor words. Words such as Proceedings, Symposium, International, Conference, Second, etc should be abbreviated to *Proc.*, *Symp.*, *Int.*, *Conf.*, *2nd*, respectively, but the rest of the title should be given in full, followed by the date of the conference and the town or city where the conference was held. For Laboratory Reports the Laboratory should be spelt out wherever possible, e.g. *Argonne National Laboratory Report.*
- The volume number, for example vol 2, should be followed by the editors, if any, in a form such as 'ed A J Smith and P R Jones'. Use *et al* if there are more than two editors. Next comes the town of publication and publisher, within brackets and separated by a colon, and finally the page numbers preceded by p if only one number is given or pp if both the initial and final numbers are given.

Examples taken from published papers:

[1] Kurata M 1982 *Numerical Analysis for Semiconductor Devices* (Lexington, MA: Heath)

[2] Selberherr S 1984 *Analysis and Simulation of Semiconductor Devices* (Berlin: Springer)

[3] Sze S M 1969 *Physics of Semiconductor Devices* (New York: Wiley-Interscience)

[4] Dorman L I 1975 *Variations of Galactic Cosmic Rays* (Moscow: Moscow State University Press) p 103

[5] Caplar R and Kulisic P 1973 *Proc. Int. Conf. on Nuclear Physics (Munich)* vol 1 (Amsterdam: North-Holland/American Elsevier) p 517

[6] Cheng G X 2001 *Raman and Brillouin Scattering-Principles and Applications* (Beijing: Scientific)

[7] Szytula A and Leciejewicz J 1989 *Handbook on the Physics and Chemistry of Rare Earths* vol 12, ed K A Gschneidner Jr and L Erwin (Amsterdam: Elsevier) p 133

[8] Kuhn T 1998 *Density matrix theory of coherent ultrafast dynamics Theory of Transport Properties of Semiconductor Nanostructures* (Electronic Materials vol 4) ed E Schöll (London: Chapman and Hall) chapter 6 pp 173–214

12. Tables and table captions

Tables should be numbered serially and referred to in the text by number (table 1, etc, **rather than** tab. 1). Each table should be a float and be positioned within the text at the most convenient place near to where it is first mentioned in the text. It should have an explanatory caption which should be as concise as possible.

12.1. The basic table format

The standard form for a table is:

```
\begin{table}
\caption{\label{label}Table caption.}
\begin{center}
\begin{tabular}{llll}
\br
Head 1&Head 2&Head 3&Head 4\\
\mr
1.1&1.2&1.3&1.4\\
2.1&2.2&2.3&2.4\\
\br
\end{tabular}
\end{center}
\end{table}
```

The above code produces table 4.

Table 4. Table caption.

Head 1	Head 2	Head 3	Head 4
1.1	1.2	1.3	1.4
2.1	2.2	2.3	2.4

Points to note are:

(1) The caption comes before the table.
(2) The normal style is for tables to be centred in the same way as equations. This is accomplished by using `\begin{center}` … `\end{center}`.
(3) The default alignment of columns should be aligned left.
(4) Tables should have only horizontal rules and no vertical ones. The rules at the top and bottom are thicker than internal rules and are set with `\br` (bold rule). The rule separating the headings from the entries is set with `\mr` (medium rule). These commands do not need a following double backslash.
(5) Numbers in columns should be aligned as appropriate, usually on the decimal point; to help do this a control sequence `\lineup` has been defined which sets `\0` equal to a space the size of a digit, `\m` to be a space the width of a minus sign, and `\-` to be a left overlapping minus sign. `\-` is for use in text mode while the other two commands may be used in maths or text. (`\lineup` should only be used within a table environment after the caption so that `\-` has its normal meaning elsewhere.) See table 5 for an example of a table where `\lineup` has been used.

Table 5. A simple example produced using the standard table commands and `\lineup` to assist in aligning columns on the decimal point. The width of the table and rules is set automatically by the preamble.

A	B	C	D	E	F	G
23.5	60	0.53	−20.2	−0.22	1.7	14.5
39.7	−60	0.74	−51.9	−0.208	47.2	146
123.7	0	0.75	−57.2	—	—	—
3241.56	60	0.60	−48.1	−0.29	41	15

13. Figures and figure captions

Figures must be included in the source code of an article at the appropriate place in the text not grouped together at the end.

Each figure should have a brief caption describing it and, if necessary, interpreting the various lines and symbols on the figure. As much lettering as possible should be removed from the figure itself and included in the caption. If a figure has parts, these should be labelled (a), (b), (c), etc. Table 6 gives the definitions for describing symbols and lines often used within figure captions (more symbols are available when using the optional packages loading the AMS extension fonts).

Table 6. Control sequences to describe lines and symbols in figure captions.

Control sequence	Output	Control sequence	Output
`\dotted`	$\cdots\cdots$	`\opencircle`	○
`\dashed`	- - - -	`\opentriangle`	△
`\broken`	– – –	`\opentriangledown`	▽
`\longbroken`	— — —	`\fullsquare`	■
`\chain`	— · —	`\opensquare`	□
`\dashddot`	— · · —	`\fullcircle`	●
`\full`	——	`\opendiamond`	◇

Authors should try and use the space allocated to them as economically as possible. At times it may be convenient to put two figures side by side or the caption at the side of a figure. To put figures side by side, within a figure environment, put each figure and its caption into a minipage with an appropriate width (e.g. 3in or 18pc if the figures are of equal size) and then separate the figures slightly by adding some horizontal space between the two minipages (e.g. `\hspace{.2in}` or `\hspace{1.5pc}`. To get the caption at the side of the figure add the small horizontal space after the `\includegraphics` command and then put the `\caption` within a minipage of the appropriate width aligned bottom, i.e. `\begin{minipage}[b]{3in}` etc (see code in this file used to generate figures 1–3).

Note that it may be necessary to adjust the size of the figures (using optional arguments to `\includegraphics`, for instance `[width=3in]`) to get you article to fit within your page allowance or to obtain good page breaks.

Using the graphicx package figures can be included using code such as:

```
\begin{figure}
```

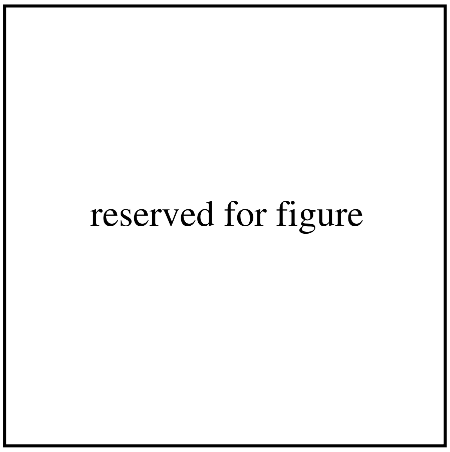

Figure 6. Figure caption for first of two sided figures.

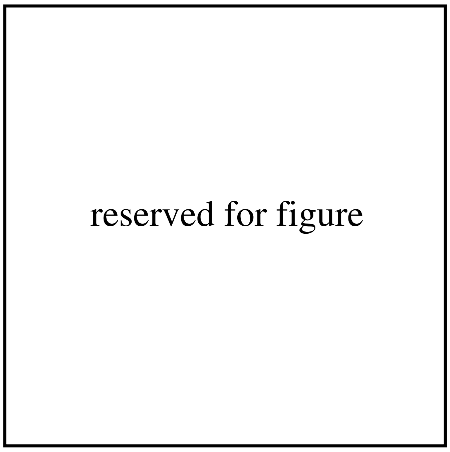

Figure 7. Figure caption for second of two sided figures.

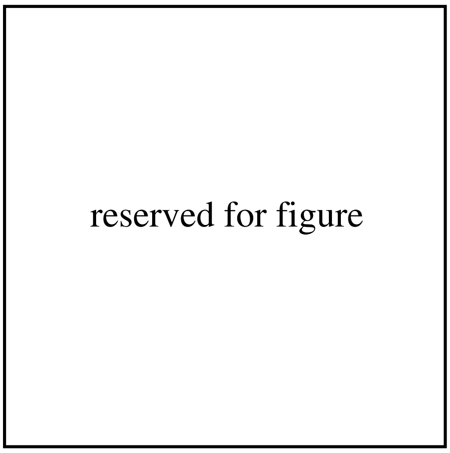

Figure 8. Figure caption for a narrow figure where the caption is put at the side of the figure.

```
\begin{center}
\includegraphics{file.eps}
\end{center}
\caption{\label{label}Figure caption}
\end{figure}
```

References

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